Document made available under the Patent Cooperation Treaty (PCT)

International application number: PCT/EP04/014796

International filing date: 29 December 2004 (29.12.2004)

Document type: Certified copy of priority document

Document details: Country/Office: US
Number: 60/626,359
Filing date: 09 November 2004 (09.11.2004)

Date of receipt at the International Bureau: 07 March 2005 (07.03.2005)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

PCT/EP2004/014796
25. 02. 2005

PA 1281008

THE UNITED STATES OF AMERICA

TO ALL TO WHOM THESE PRESENTS SHALL COME:

UNITED STATES DEPARTMENT OF COMMERCE

United States Patent and Trademark Office

February 08, 2005

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE UNDER 35 USC 111.

APPLICATION NUMBER: ***60/626,359***
FILING DATE: ***November 09, 2004***

By Authority of the
COMMISSIONER OF PATENTS AND TRADEMARKS

M. Sias

M. SIAS
Certifying Officer

20427 U.S. PTO
110904

[40124/04101

17513 U.S. PTO
60/626359
110904

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventor(s)	:	**Lutz MAY** **Wolfratshauser Str. 23a** **82578 Geretsried-Gelting** **Germany** **Citizenship: Germany**
Serial No.	:	**To Be Assigned**
Filing Date	:	**Herewith**
For	:	**A METHOD AND AN APPARATUS FOR MAGNETIZING AN OBJECT, A METHOD AND AN APPARATUS FOR CALIBRATING A FORCE AND TORQUE SENSOR DEVICE, A USE OF AN APPARATUS FOR MAGNETIZING AN OBJECT IN PARTICULAR TECHNICAL FIELDS, AND USE OF AN APPARATUS FOR CALIBRATING A FORCE AND TORQUE SENSOR DEVICE IN PARTICULAR TECHNICAL FIELDS**

Mail Stop: New Patent Application
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Please associate this application (Attorney Docket No. 40124/04101) with Customer No. 30636

Express Mail Certificate

"Express Mail" Mailing Label No. EV 410 625 775 US

Date of Deposit November 9, 2004

I hereby certify that this correspondence is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above and is addressed to: Commissioner for Patents, PO Box 1450, Alexandria, VA 22313-1450

Name: Patrick J. Fay , Reg. No. 35,508

Signature

U.S. PROVISIONAL APPLICATION REQUEST TRANSMITTAL

Enclosed herewith please find the following:

1. **1** sheet of Title Page and **69** sheets of Specification.
2. **34** sheets of drawings.
3. Return Receipt Postcard.

A check in the amount of **$160.00** is enclosed herewith. The Commissioner is hereby authorized to charge the Deposit Account of **Fay Kaplun & Marcin, LLP No. 50-1492** any additional fees associated with this communication or arising during the pendency of this application. A copy of this Transmittal is submitted for this purpose.

Date: November 9, 2004

By: ______________________
Patrick J. Fay (Reg. No. 35,508)

Fay Kaplun & Marcin, LLP
150 Broadway, Suite 702
New York, NY 10038
(212) 619-6000- Telephone
(212) 619-0276- facsimile

[40124/04101]

U.S. PROVISIONAL PATENT APPLICATION

For

A METHOD AND AN APPARATUS FOR MAGNETIZING AN OBJECT, A METHOD AND AN APPARATUS FOR CALIBRATING A FORCE AND TORQUE SENSOR DEVICE, A USE OF AN APPARATUS FOR MAGNETIZING AN OBJECT IN PARTICULAR TECHNICAL FIELDS, AND USE OF AN APPARATUS FOR CALIBRATING A FORCE AND TORQUE SENSOR DEVICE IN PARTICULAR TECHNICAL FIELDS

Inventor(s):

Lutz MAY

Total Pages (including title page and specification): 70

Represented by:
FAY KAPLUN & MARCIN, LLP
150 Broadway, Suite 702
New York, NY 10038
(212) 619-6000 (tel)
(212) 619-0276 (fax)
info@FKMiplaw.com

Express Mail Certificate

"Express Mail" Mailing Label No. EV 410 625 775 US

Date of Deposit November 9, 2004

I hereby certify that this correspondence is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above and is addressed to: Commissioner for Patents, PO Box 1450, Alexandria, VA 22313-1450

Name: Patrick J. Fay, Reg. No. 35,508

Signature

Application No.	Our Reference	Munich,
New Application	N 7179 / KK	8. November 2004
NCTENGINEERING GMBH		

NCTEngineering GmbH

Otto-Hahn-Straße 24, 85521 Ottobrunn, Deutschland

A method and an apparatus for magnetizing an object, a method and an apparatus for calibrating a force and torque sensor device, a use of an apparatus for magnetizing an object in particular technical fields, and a use of an apparatus for calibrating a force and torque sensor device in particular technical fields

---

Background of the Invention

Field of the Invention

KK:AD

The present invention relates to a method and an apparatus for magnetizing an object, to a method and an apparatus for calibrating a force and torque sensor device, to a use of an apparatus for magnetizing an object in particular technical fields, and to a use of an apparatus for calibrating a force and torque sensor device in particular technical fields.

Description of the Related Art

Magnetic transducer technology finds application in the measurement of torque and position. It has been especially developed for the non-contacting measurement of torque in a shaft or any other part being subject to torque or linear motion. A rotating or reciprocating element or an element which is subject to an axial load or to shear forces can be provided with a magnetized region, i.e. a magnetic encoded region, and when the shaft is rotated or reciprocated, such a magnetic encoded region generates a characteristic signal in a magnetic field detector (like a magnetic coil) enabling to determine torque, force or position of the shaft.

For such kind of sensors which are disclosed, for instance, in WO 02/063262, it is important to have an accurately defined magnetically encoded region which can be manufactured and calibrated with low cost.

Summary of the Invention

It is an object of the present invention to provide a sensor device having a magnetically encoded region, wherein the sensor device shall be manufacturable and operable with low cost.

This object is achieved by providing a method and an apparatus for magnetizing an object, a method and an apparatus for calibrating a force and torque sensor device, a use of an apparatus for magnetizing an object in particular technical fields, and a use of an apparatus for calibrating a force and torque sensor device in particular technical fields according to independent aspects of the invention as mentioned in the following.

In the following, different aspects of the invention will be described.

Aspects 1, 10, 28, 29, 33, and 34 are independent aspects of the invention which may be realized with or without any other means. Aspects 2 to 9 relate to preferred embodiments of aspect 1. Aspects 11 to 27 relate to preferred embodiments of aspect 10. Aspects 30 and 32 relate to preferred embodiments of aspect 29.

1. aspect: A method for magnetizing a first object and/or a second object, the method comprising the steps of

arranging a first object in such a manner that the first object encloses a second object;

applying a first electrical signal to the second object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized.

2. aspect: The method according to aspect 1,
wherein the first electrical signal is a first pulse signal or a sequence of subsequent pulse signals.

3. aspect: The method according to aspect 2,
wherein, in a time versus current diagram, the first pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge.

4. aspect: The method according to any of aspects 1 to 3,
wherein the first electrical signal is a current or a voltage.

5. aspect: The method according to any of aspects 1 to 4,
wherein a second electrical signal is applied to the second object after having applied the first electrical signal, wherein the second electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized, and wherein the second electrical signal differs from the first electrical signal concerning at least one of the group consisting of amplitude, sign, signal shape and duration.

6. aspect: The method according to aspect 5,
wherein the second electrical signal is a second pulse signal or a sequence of subsequent pulse signals.

7. aspect: The method according to aspect 6,
wherein, in a time versus current diagram, the second pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge.

8. aspect: The method according to any of aspects 5 to 7,
wherein the first object and/or the second object is magnetized by applying the first electrical signal and the second electrical signal such that in a direction essentially perpendicular to a surface of the first object and/or of the second object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction.

9. aspect: The method according to any of aspects 5 to 8,
wherein the second electrical signal is a current or a voltage.

10. aspect: An apparatus for magnetizing a first object and/or a second object, the apparatus comprising

a first object;

a second object;

an electrical signal source;

wherein the first object is arranged in such a manner that the first object encloses the second object;

wherein the electrical signal source is adapted to apply a first electrical signal to the second object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized.

11. aspect: The apparatus according to aspect 10,
wherein the first object is a hollow tube.

12. aspect: The apparatus according to aspect 10 or 11,
wherein the second object is one of the group consisting of a shaft, a wire and a hollow tube.

13. aspect: The apparatus according to any of aspects 10 to 12,
wherein the second object is arranged at a center of the first object.

14. aspect: The apparatus according to any of aspects 10 to 13,
wherein the electrical signal source comprises a capacitor bank.

15. aspect: The apparatus according to any of aspects 10 to 14,
wherein the first object has a first electrical connection and has a second electrical connection, wherein the second object has a first electrical connection and has a second electrical connection, and wherein the second electrical connection of the first object is coupled to the first electrical connection of the second object.

16. aspect: The apparatus according to aspect 15,
wherein the electrical signal source is connected such that a first electrical signal is applyable between the first electrical connection of the first object and the second electrical connection of the second object.

17. aspect: The apparatus according to aspect 15,
wherein the first object has a third electrical connection, wherein the second object has a third electrical connection.

18. aspect: The apparatus according to aspect 17,
wherein the electrical signal source is connected such that a first electrical signal is applyable between the first electrical connection of the first object and the second electrical connection of the second object, and such that a second electrical signal is applyable between the third electrical connection of the first object and the third electrical connection of the second object.

19. aspect: The apparatus according to any of aspects 15 to 18,
further comprising an electrically conductive coupling element arranged to couple the second electrical connection of the first object to the first electrical connection of the second object.

20. aspect: The apparatus according to aspect 19,
wherein the coupling element is an electrically conductive plate or an electrically conducting liquid.

21. aspect: The apparatus according to any of aspects 10 to 20,
wherein the second object, in addition to the first object, is adapted to be magnetized when the first electrical signal is applied.

22. aspect: The apparatus according to any of aspects 10 to 14,
wherein the second object comprises a first connection and a second connection, wherein the electrical signal source is connected between the first connection and the second connection of the second object.

23. aspect: The apparatus according to any of aspects 10 to 14, or 22,
wherein the electrical signal source is disconnected from the first object.

24. aspect: The apparatus according to aspect 22 or 23,
wherein a portion of the second object is free from an enclosure with the first object, further comprising a shielding element which is arranged and adapted to electromagnetically shield the portion of the second object being free from an enclosure with the first object from the first object.

25. aspect: The apparatus according to aspect 24,
wherein the shielding element is arranged between the first element and the portion of the second object being free from an enclosure with the first object.

26. aspect: The apparatus according to aspect 24,
wherein the shielding element is a tube which is arranged to enclose the portion of the second object being free from an enclosure with the first object.

27. aspect: The apparatus according to aspect 24,
wherein the shielding element comprises a plurality of sub-elements which are arranged surrounding the portion of the second object being free from an enclosure with the first object.

28. aspect: A method for calibrating a force and torque sensor device, the method comprising the steps of

providing a force and torque sensor device having a magnetically encoded region on an object and a magnetic field detector adapted to detect a signal resulting from a force or a torque applied to the object;

applying a pre-known force to the object;

detecting a signal resulting from the pre-known force applied to the object;

calibrating the force and torque sensor device based on a correlation between the pre-known force and the detected signal resulting from the pre-known force.

29. aspect: An apparatus for calibrating a force and torque sensor device, the apparatus comprising

a force and torque sensor device;

a pre-known force generating element;

a calibrating unit;

wherein the force and torque sensor device has a magnetically encoded region on an object and a magnetic field detector adapted to detect a signal resulting from a force or a torque applied to the object;

wherein the pre-known force generating element is adapted to apply a pre-known force to the object;

wherein the calibrating unit is adapted to calibrate the force and torque sensor device based on a correlation between a pre-known force and a detected signal resulting from the pre-known force.

30. aspect: The apparatus according to claim 29,
wherein the pre-known force generating element is a pre-known weight.

31. aspect: The apparatus according to claim 29,
wherein the pre-known force generating element is adapted to apply a pre-known shear stress.

32. aspect: The apparatus according to claim 29,
wherein the pre-known force generating element is a pre-known torque.

33. aspect: Using an apparatus according to any of aspects 10 to 27 for magnetizing one of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, and a shaft of an engine.

34. aspect: Using an apparatus according to any of aspects 29 to 32 for calibrating a force and torque sensor device of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, and a shaft of an engine.

In the following, the above mentioned independent aspects of the invention will be described in more detail.

Within this specification, the expression "magnetizing" particularly has the meaning that microscopic or elementary magnets like magnetic moments, grains or domains which are present within a magnetizable material are treated such that at least a part of them becomes aligned along a particular direction, so that a random magnetic orientation is at least partially removed.

The method for magnetizing a first object and the apparatus for magnetizing a first object according to the independent aspects mentioned above have the advantage that a first object can be magnetized by applying an electrical signal to a second object which is surrounded by the first object. For instance, a wire or a shaft or a rod as the second element can be surrounded by a hollow cylinder as the first object. Applying an appropriate electrical signal to the second object then allows to generate a magnetized region in the first object due to a physical effect which is similar like the physical effects occurring in the case of a transformator. In other words, a time-dependent electrical signal, like a current pulse, flowing

through the second object generates a magnetic field which influences magnetizable material of the first object in such a manner that it becomes magnetized. The magnetization scheme of the invention allows a cheap and easy magnetization even of large hollow cylinders – as they occur particularly in the field of mining and drilling equipment. Thus, a magnetically encoded region can be formed in an already existing industrial steel hollow cylinder or tube. This allows that also already existing magnetizable objects, for instance a drilling shaft, may be provided with a magnetically encoded region so that a torque, a bending force and an axial load applied to such an object can be measured by a simple magnetic field detector like a coil arranged adjacent to the magnetized object.

According to the described embodiment, particularly the outer first object is magnetized. However, in case that also the inner second object is made of a magnetizable material, the second object is magnetized simultaneously.

Another advantage related to the method and the apparatus for magnetizing a second object according to the independent aspects of the invention is the opportunity to connect the first object to the second object at a selected position, for instance at an end portion of the first object and at an end portion of the second object. According to such an architecture, the current flowing through the second object is injected also in the first object to form a counter magnetic field there, which stabilizes the current distribution in the objects. Thus, a high quality magnetically encoded region may be formed in the second object, yielding a sensor with more reproducible and reliable properties.

According to the described embodiment, particularly the inner second object is magnetized. However, in case that also the outer first object is made of a magnetizable material, the first object is magnetized simultaneously.

In the following, the method and the apparatus for calibrating a force and torque sensor device will be explained. An important idea of this calibrating method is to simply apply a pre-known calibrating force, for instance a known mass or weight, to an object having a magnetically encoded region (which may be generated, for instance, according to the method of the invention of magnetizing an object). Such a weight or gravity force applied to a torque and force sensor results in a magnetic signal which can be detected by a magnetic field detector arranged in the vicinity of the magnetically encoded region. Therefore, the correlated data pair of the applied force and the resulting detection signal of the magnetic field detector can be stored. The magnetically encoded region can be encoded, for instance, according to the above described method of magnetizing an object, or to the technology mentioned in WO 02/063262, or according to the so-called PCME technology which will be described below in detail.

The thus measured correlation between an axial load and a detected signal of the magnetic field detector can then be used for a calibration of the sensor. When the object calibrated in this manner is practically used (for instance as a drilling shaft), a measured detection signal can be associated with an corresponding axial load force, using the calibration data pair estimated using the known mass. It is also possible, during calibration, to measure a plurality of calibration data pairs to refine the calibration.

Further, the data pair of a known axial load and a corresponding detecting signal may also serve as an calibration information which may be used with a sensor which is subject of an applied torque during practical use. In other words, an axial load calibration calibrates a torque sensor. This aspect is particularly advantageous in an application in which a very heavy object is used, for example in the context of a drilling shaft in a mining application, when the torque applied to such a drilling shaft shall be measured. In this case, it is very easy just to place the drilling shaft, for example a tube, on a stable ground base and to put a known mass element on the upper end of the drilling shaft. In contrast to this, it would be very

difficult to apply a calibration torque to such a drilling shaft for calibrating a torque sensor. It is easier to calibrate a torque sensor by using a calibrating axial force.

According to further independent aspects of the invention, the methods and apparatuses mentioned above may be implemented in the frame of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, or a shaft of an engine. In all of these applications, the magnetization and the calibration of such a torque, force and position sensor is highly advantageous, since it allows to manufacture a highly accurate and reliably calibrated force, position and torque sensor with low costs. Particularly, mining and drilling equipment may be provided with the systems of the invention, and may be used for monitoring a drilling direction and drilling forces. Further applications of the invention are the recognition and the analysis of engine knocking.

Thus, a real-time measurement of actual mechanical forces applied and being effective "on the job" of large mining and drilling equipment is enabled according to the invention. The harsh outdoor conditions and dealing with abrasive materials is something traditional sensing technologies have difficulties to deal with, whereas the systems of the invention are compatible with such conditions without any problems. Mechanical forces which may be measured according to the invention are torque, bending, axial load and potential mining equipment overloads.

By the magnetization method of the invention, a unique power-shaft encoding process is employed which allows utilizing the magnetic properties of many types of industrial steel so that a standard drilling shaft turns into a high precision force sensor. The actual time required to apply the encoding process is a fraction of a second and is permanent. After the desired section of the drilling shaft has been treated with the process of the invention, this part of the shaft is emanating a specific signal in relation to the applied mechanical forces to the shaft. This signal can be detected, for instance, by a passive electrical component that is placed

several millimetres away from the shaft surface. Nothing needs to be attached to the shaft and nothing needs to touch the shaft, therefore the mean time between failure is very high (i.e. the invention provides a very reliable sensing solution). This non-contact mechanical force measurement principle relies only on the ferromagnetic properties of the drilling or power-transmitting shaft. It provides real-time information of any mechanical force that is travelling through the encoded section of the shaft, including rotational torque, bending forces, shearing forces and axial push-pull load. The overall signal bandwidth of the force-sensing technology is, according to an embodiment, 29kHz or around 100,000 measurement samples per second. In addition, a distinct signal will be emitted when the drilling shaft has been exposed to mechanical overload and is about to fail.

In large equipment it is often the case that the mechanical forces do not travel symmetrically or even distributed through the power or drilling shaft. Therefore, the magnetic field detector preferably "looks" at several critical locations at the shaft to get a larger picture. However, particularly in statically operating equipment (where the shaft does not rotate) it is often recommendable to work with one magnetic detecting device only.

The sensor of the invention can operate under water, in oil, or even in very dusty environment (like in concrete pumps or concrete mixing stations). The sensor can withstand temperatures in a very large range, particularly from –50°C to +210°C.

The sensor signal detection units may be connected to a custom specific electronic circuit that can be placed several metres away from the magnetic field detectors itself. Only two wires ("twisted pair") may be implemented to connect a magnetic field detector with a corresponding electronic circuit. The output signal of such an electronic circuit can be a buffered analogue +5V signal, whereby +2500V may equal to zero torque. The overall electrical current consumption for a torque, axial load, or bending sensor is less than 5 mA per sensor channel.

The magnetic field detectors may be placed outside or inside a magnetically encoded hollow shaft. Assuming that mechanical forces transmitted through such a shaft are not passing through the magnetically encoded section symmetrically, several magnetic field detectors may be placed geometrically around the shaft to be able to capture a highly resolved "force picture".

The encoding of large drilling shafts may be done "at site" to eliminate the potential need of shipping the heavy shaft to a specific factory location. The encoding equipment may be portable/mobile and can be used under almost all weather conditions. Under ideal circumstances, the drilling shaft can be placed on its own onto the ground for the encoding process. However, under the correct circumstances, the drilling shaft can be encoded while still placed in the drilling or mining equipment. This is particularly possible if the shaft can be accessed and is not hidden away. Such a mobile magnetizing and calibration unit can be brought very close to a drilling shaft.

An important feature of the sensing technology according to the invention is the way the permanent encoding drilling shaft may be calibrated. In case of a one meter diameter drilling shaft which is capable to deal with one million Nm torque, it will be normally be difficult to apply a "beam and weight" method for the shaft torque sensor calibration. When placing upright on a horizontal and structurally sound surface, the measurement performances of the magnetically encoded shaft can be defined within a relative short time by relying on the way the "permanently" embedded signal source is behaving. This is particularly of interest when the drilling equipment has to be serviced and maintained at remote and difficult to reach locations.

The mechanical force sensing technology according to the invention can be implemented in large-scale oil drilling equipment to detect the direction the drilling head is moving, and to

measure the drilling pipes axial load (forward thrust) at the drilling heads location. In this application, the entire sensor system may be exposed to pressures of >1,500 bars and to temperatures >200°C. In another application, the sensing principle is measuring the mechanical forces applied to large-scale mobile/moving cranes. Here, the magnetically encoded sensor has the task to prevent the crane from falling (falling over or tilting) when critical load situations occur. Other applications of the invention are wind power plants, large extruder equipment, abrasive material pumping station, and large-scale industrial gear box systems.

It is mentioned that – as an alternative to the first independent aspect - a second object (e.g. a shaft) enclosed by a first object (e.g. a hollow tube) can be magnetized by applying an electrical signal to the first object. This aspect is related to a method for magnetizing a second object, the method comprising the steps of arranging a first object in such a manner that the first object encloses the second object, and applying an electrical signal to the first object, wherein the electrical signal is adapted such that at least a portion of the second object is magnetized. The method works particularly fine when end portions of the second object outside the first object are short-circuited, for instance if two such end portions are connected with each other electrically be a wire guided outside of the first object.

In the following, preferred embodiments of the method for magnetizing an object according to the first independent aspect of the invention will be described. However, these embodiments also apply for the apparatus for magnetizing an object, for the method and the apparatus for calibrating a force and torque sensor device, for the use of an apparatus for magnetizing an object in particular technical fields, and for the use of an apparatus for calibrating a force and torque sensor device in particular technical fields, according to other independent aspects of the invention.

The first electrical signal may be a first pulse signal or a sequence of subsequent pulse signals. Such a pulse signal can particularly be a signal which is different from zero only for a defined interval of time.

Preferably, in a time versus current diagram, the first pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge. With such a pulse signal, the magnetically encoded region obtained has a high quality. It is also possible that a plurality of such pulses are subsequently applied to form a magnetically encoded region.

A second electrical signal may be applied to the second object after having applied the first electrical signal, wherein the second electrical signal may be adapted such that at least a portion of the first object and/or of the second object is magnetized, and wherein the second electrical signal differs from the first electrical signal concerning at least one of the group consisting of amplitude, sign, signal shape and duration.

According to this embodiment, two pulses with opposite flowing direction of the electrical current may be applied to the second object.

The second electrical signal may be a second pulse signal or a sequence of subsequent pulse signals, which, in a time versus current diagram may have a fast raising edge which is essentially vertical and may have a slow falling edge.

According to an embodiment of the method of the invention, the first object may be magnetized by applying the first electrical signal and the second electrical signal such that in a direction essentially perpendicular to a surface of the first object and/or of the second object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction. This geometrical orientation of the two layers of

magnetization results from two different pulses applied to the magnetizable material, so that a PCME-like sensor according to the below described technology may be manufactured.

The second electrical signal may also be an electrical current or an electrical voltage.

In the following, preferred embodiments of the apparatus for magnetizing an object according to the second independent aspect of the invention will be described. However, these embodiments also apply for the method for magnetizing an object, for the method and the apparatus for calibrating a force and torque sensor device, for the use of an apparatus for magnetizing an object in particular technical fields, and for the use of an apparatus for calibrating a force and torque sensor device in particular technical fields, according to other independent aspects of the invention.

The first object may be a hollow tube. For instance, the first object enclosing the second object may be a hollow cylinder or the like. This structure provides a very symmetric geometry and is easy to manufacture. However, the first object being arranged as a hollow tube does not necessarily have to have a circular cross-section, but may also have a cross-section with the geometry of a polygon (e.g. a triangle or a square). Such a more asymmetric configuration may be used to refine sensing properties.

The second object may be a wire or a shaft or a hollow tube. Such a shaft or wire may be arranged along a symmetry axis of the first object, particularly of the first object embodied as a hollow tube. In an embodiment in which the second object is a hollow tube, the radius of the hollow tube as the second object is smaller than the radius of the hollow tube as the first object so that the second object can be surrounded by the first object. The second object being arranged as a hollow tube does not necessarily have to have a circular cross-section, but may also have a cross-section with the geometry of a polygon (e.g. a triangle or a square). Such a more asymmetric configuration may be used to refine sensing properties.

The second object may be arranged at a centre of the first object. In this configuration, a very symmetric current and magnetic field distribution is achieved.

The electrical signal source may comprise a capacitor bank. Such a capacitor bank comprises a plurality of capacitors which together may generate a pulse signal with a very high current amplitude and a small time duration, particularly for magnetizing large objects, as they may occur in the field of mining and drilling equipment. Such a capacitor bank may, for instance, have a capacity of 0.5 F. As an alternative to a capacitor bank, the electrical signal source/ electrical power source may comprise a conventional power supply unit or power pack.

The first object may have a first connection and may have a second connection, and the second object may have a first electrical connection and a second electrical connection. The second electrical connection of the first object may be coupled to the first electrical connection of the second object. According to this embodiment, the two objects are coupled in a manner that a portion, preferably an end portion, of the first object is coupled to a portion, preferably an end portion, of the second object. By this configuration, the current flowing through the second object is injected into the first object, so that a "feedback" of the magnetic field generating current is achieved. By this feedback, a counter magnetic field is generated in the first object which, together with the current flowing through the second object, provides a very symmetric configuration and yields an advantageous current distribution within the object. A torque and force sensor with a magnetic encoding of this kind, has a very high signal to noise ratio and only a small hysteresis behaviour.

Referring to the previously described embodiment, the electrical signal source may be connected such that a first electrical signal is applyable between the first electrical connection of the first object and the second electrical connection of the second object. According to this circuitry, the current is flowing from the first electrical connection of the first object to the

second electrical connection of the first object, from there to the first electrical connection of the second object, and from there to the second electrical connection of the second object.

The first object may have a third electrical connection, and the second object may have a third electrical connection.

Referring to this embodiment, the electrical signal source may be connected such that a first electrical signal is applyable between the first electrical connection of the first object and the second electrical connection of the second object, and such that a second electrical signal is applyable between the third electrical connection of the first object and the third electrical connection of the second object. This configuration allows to apply magnetizing currents from both end portions of the first and second objects, whereas the first and second objects are coupled electrically at their centre portions with each other.

The apparatus may further comprise an electrically conductive coupling element arranged to couple the second electrical connection of the first object to the first electrical connection of the second object. Such a coupling element may be an electrically conductive plate, like a metal plate, which may be coupled with an end portion of a shaft as the second object and coupled with an end surface of a hollow tube as the first object. However, the electrically conductive coupling element may also be realized as a simple wire or the like. The electrically conductive coupling element may also be realized as an electrically conducting liquid, e.g. on the basis of mercury.

The second object, in addition to the first object, may be adapted to be magnetized when the first electrical signal is applied. In other words, according to the described arrangement of the first object enclosing the second object, both of the objects can be magnetized and used as magnetized objects of a torque or force sensor.

The second object may comprise a first connection and a second connection, wherein the electrical signal source may be connected between the first connection and the second connection of the second object. According to this circuitry, the electrical signal source may be disconnected from the first object. In other words, this configuration can be considered as a transformator-like arrangement, wherein the first object surrounding the second object can be magnetized without any direct ohmic contact between the two objects. In this context, the magnetization of the first object is generated by the electrical signal propagating through the second object and forcing elementary magnets of the material of the first object to become aligned.

According to a preferred embodiment, a portion of the second object may be free from an enclosure with the first object, and the apparatus may further comprise a shielding element which is arranged and adapted to electromagnetically shield the portion of the second object being free from an enclosure with the first object from the first object. This embodiment takes into account that a wiring of the second object back to the electrical signal source may also produce a magnetic field which influences the first object in a way that the magnetization generated by the part of the second object being enclosed or surrounded by the first object is weakened. In order to avoid such an undesired weakening and to achieve a homogeneous and reproducible magnetization of the first object, the shielding element shields the magnetic field generated by the part of the wiring of the second object which is not covered by the first object.

Such a shielding element may be an element, for instance a tube, which may be optionally made of a magnetizable material which is arranged between the first object and the portion of the second object being from an enclosure with the first object. In this configuration, the shielding element forms some kind of magnetic "shadow" to magnetically decouple the first object from the part of the second object which is not covered by the second object.

Alternatively, the shielding element may be a tube (optionally made of a magnetizable material) which is arranged to enclose the portion of the second object being free from an enclosure with the first object. According to this embodiment, the shielding tube surrounds at least a part of the part of the second object which is not surrounded by the first element.

As a further alternative, the shielding element may comprise a plurality of tubes (optionally made of a magnetizable material) which are arranged surrounding at least a part of the portion of the second object being free from an enclosure with the first object. Such shielding tubes may be arranged symmetrically around the part of the first object to be shielded.

In the following, preferred embodiments of the apparatus for calibrating a force and torque sensor device according to the forth independent aspect of the invention will be described. However, these embodiments also apply for the method and apparatus for magnetizing an object, for the method for calibrating a force and torque sensor device, for the use of an apparatus for magnetizing an object in particular technical fields, and for the use of an apparatus for calibrating a force and torque sensor device in particular technical fields, according to other independent aspects of the invention.

In the calibrating apparatus, the pre-known force generating element may be a pre-known weight. This pre-known weight, for instance 1000 kg, may be simply put on the top of a hollow cylinder-like force and torque sensor device to be calibrated and forms a constant and pre-known axial load applied to the sensor device, so that a highly accurate calibration is possible.

Alternatively, the pre-known force generating element may be adapted to apply a pre-known shear stress. Also by applying a shear stress, a pair of data values (force; resulting magnetic signal) can be obtained as a basis for a calibration.

Alternatively, the pre-known force generating element may be adapted to be a pre-known torque, particularly a pre-known reactive torque.

The above and other aspects, objects, features and advantages of the present invention will become apparent from the following description and the appended claim, taken in conjunction with the accompanying drawings in which like parts or elements are denoted by like reference numbers.

Brief Description of the Drawings

The accompanying drawings, which are included to provide a further understanding of the invention and constitute a part of the specification illustrate embodiments of the invention.

In the drawings:

Fig. 1A shows a magnetizing apparatus without involving an object enclosing another object,

Fig. 1B shows a magnetizing apparatus according to the invention involving an object enclosing another object,

Fig. 1C shows a schematic view of a torque and force sensing device with a magnetically encoded region formed according to the invention,

Fig. 1D shows a signal versus torque diagram of a torque and force sensing device magnetized with the magnetizing apparatus shown in Fig. 1A,

Fig. 1E shows a signal versus torque diagram of a torque and force sensing device magnetized with the magnetizing apparatus shown in Fig. 1B,

Fig. 2 is a schematic view illustrating the principle of a method for magnetizing an object according to the invention,

Figs. 3A and **3B** are schematic views illustrating an apparatus for magnetizing an object according to the invention,

Fig. 3C is a schematic view illustrating another apparatus for magnetizing an object according to the invention,

Fig. 3D is a diagram illustrating a pulse signal for magnetizing a object according to an apparatus as shown in Figs. 3A to 3C,

Figs. 4A, 4B illustrate another embodiment of an apparatus for magnetizing an object according to the invention,

Fig. 5 illustrates still another apparatus for magnetizing an object according to an embodiment of the invention,

Figs. 6A to **6D** show top views of different apparatuses for magnetizing an object according to embodiments of the invention,

Fig. 7 shows another apparatus for magnetizing an object according to the invention,

Figs. 8A, 8B show different views of an apparatus for calibrating a force and torque sensor device according to the invention,

Figs. 9A, 9B show schematic views of force and torque sensor devices according to the invention,

Fig. 10 shows different views of magnetically encoded hollow cylinders,

Fig. 11 shows views of a sensing device according to the invention,

Fig.12 to **Fig.67** illustrate the PCME technology which, according to the invention, is preferably used to magnetize a magnetizable object.

Fig. 68 illustrates still another apparatus for magnetizing an object,

Fig. 69 illustrates still another apparatus for magnetizing an object according to an embodiment of the invention,

Fig. 70 shows another apparatus for calibrating a force and torque sensor device according to the invention.

Detailed Description of Preferred Embodiments of the Invention

Fig. 1A shows a magnetizing apparatus 140 for magnetizing a shaft 150 to form a magnetically encoded region on the shaft 150. The magnetizing apparatus 140 does not involve a shaft which is enclosed by another object. When a current signal is applied between different ends of the shaft 150, the shaft 150 is magnetized.

Fig. 1B shows a magnetizing apparatus 160 according to the invention involving a hollow tube 121 enclosing a shaft 150 (not shown in Fig. 1B) to be magnetized. An end portion of the shaft 150 is coupled with an end portion of the hollow tube 121 enclosing the shaft 150. When a current signal is applied to the shaft 150, the current is injected in the hollow tube 121. The magnetic field generated by the current flowing in the hollow tube 121 stabilizes the current distribution in the shaft 150. Thus, the shaft 150 is magnetized in a very homogenous manner.

Fig. 1C shows a schematic view of a torque and force sensing device 170 with a magnetically encoded region 122 formed according to the magnetization generation process carried out with the magnetizing apparatus 160. The length of the magnetically encoded region 122 is defined by the length along which the current flows during the magnetization procedure (i.e. depends on the geometry of the contacts for injecting a magnetizing current).

Fig. 1C shows the torque sensor 170 having the shaft 150 which may rotate with a predetermined value of torque, wherein a portion of the shaft 150 is magnetized to form a magnetically encoded region 122. When the shaft 150 rotates, the magnetically encoded region 122 generates a magnetic signal in a magnetic field detecting coil 123.

Fig. 1D shows a signal versus torque diagram 100 (an experimentally measured curve and a schematic curve emphasizing the features of the measured curve) of a torque and force sensing device magnetized with the magnetizing apparatus 140 shown in Fig. 1A.

Fig. 1E shows a signal versus torque diagram 110 (an experimentally measured curve and a schematic curve emphasizing the features of the measured curve) of a torque and force sensing device 170 magnetized with the magnetizing apparatus 160 shown in Fig. 1B.

The diagrams 100, 110 of Fig. 1D and Fig. 1E each have an abscissa 101 along which a torque is shown which is applied to a shaft with a magnetically encoded region. Figs. 1D and

1E show along an ordinate 102 the signal as detected by coil 123 when a particular value of the torque as plotted along the abscissa 101 is applied.

Figs. 1D and 1E show a hysteresis loop 103 and a best fit line 104, for both cases. As can be seen, the slope of the best fit line 104 is larger in Fig. 1E than in Fig. 1D, and the hysteresis properties are suppressed in Fig. 1E even better than in Fig. 1D.

One of the big challenges of the magnetic field encoding process according to the invention is to achieve a uniform electrical current distribution around a "to be encoded" shaft 150, i.e. to have a properly magnetized region 122. Failing to do so will result in a poor rotational signal uniformity performance and in a poor signal linearity.

Fig. 1D shows the sensors torque signal when the shaft 150 has been processed according to Fig. 1A. The sensor characteristics as shown in Fig. 1D shows some non-linearity which has a negative impact on the sensor signal hysteresis performance.

Processing the shaft 150 to form the magnetically encoded region 122 with the method as shown in Figs. 1B, 2, 3, greatly improves the sensors signal linearity and has a positive impact on the sensors signal hysteresis, which will become much smaller (see Fig. 1E).

The magnetically encoded sensor corresponding to Fig. 1A has a slope of the best fit line 104 of 13.8 mV/Nm, and a hysteresis of 3.72%. In contrast to this, the torque sensor magnetized according to Fig. 1B has, as shown in Fig. 1E, a slope of 15.1 mV/Nm and a hysteresis with only 2.59%.

Thus, the signal-to-noise ratio is significantly improved when the magnetically encoded region 122 is generated according to the invention.

A basic principle of the method for magnetizing an object according to the invention, which can also be denoted as a self-adjusting process, is to generate a counter magnetic field during the actual magnetization process, whereby this counter magnetic field ensures that the electrical signal passes through the shaft 150 very uniformly through the "to be encoded" sensing region 122.

By passing back the electrical signal for magnetizing a part of the shaft 150 to form the magnetically encoded region 122 through the conductive tube 121 enclosing the shaft 150, the magnetic field that develops at the inner side of the tube 121 can work hand in hand with the magnetic field that is developing at the outside of the shaft 150. The shaft 150 is placed at the centre, inside the tube 121, and is not allowed to contact the tube 121, except at desired locations.

Fig. 2 shows a scheme which may be useful for a further understanding of the invention. Thus, the arrangement shown in Fig. 2 shows the solid shaft 150 and the hollow tube 121. An electrical current I is injected in the solid shaft 150 to form a magnetic field around the solid shaft 150, as shown in Fig. 2. When this current I flows through the hollow tube 121, a further magnetic field is also generated in the material of the hollow tube 121. Thus, Fig. 2 is a schematic view illustrating a principle of a method for magnetizing an object according to the invention.

Figs. 3A and **3B** are schematic views illustrating an apparatus for magnetizing an object according to the invention.

In order to magnetize the shaft 150, the hollow tube 121 is arranged to enclose the solid shaft 150. Further, an electrical signal I is applied to the solid shaft 150. As shown in a diagram 310 of Fig. 3D having a time abscissa 301 and having a current ordinate 302, the pulsed current signal 300 has a fast raising edge which is essentially vertical and has a slow falling edge.

As can be further seen in Fig. 3A, the solid shaft 150 is arranged at the centre of the hollow tube 121. The hollow tube 121 has first electrical connection 201 and has a second electrical connection 202, wherein the second electrical connection 202 of the hollow tube 121 is coupled to a first electrical connection 203 of the solid shaft 150. Further, the solid shaft has a second electrical connection 204. An electrical signal source (not shown) is connected such that the current signal I can be applied between the first connection 201 of the hollow tube 121 and the second connection 204 of the solid shaft 150.

Fig. 3B shows another view of the configuration of Fig. 3A.

Because the magnetic flux direction at the inside of the hollow tube 121 (caused by the return electrical current flow direction) is the same rotational direction as the magnetic field that goes around the solid shaft 150 (because of the forward electrical current flow direction), the magnetic field density will distribute itself uniformly in the space between the tube 121 and the shaft 150. Consequently, the electrical current that flows in the solid shaft 150 and the tube 121 will be evenly distributed in both items.

The resulting solution is that the rotational signal uniformity performance of the sensor signal improves greatly (see Fig. 1E), and with this the signal non-linearity and signal hysteresis (will become smaller), and in addition the signal slope increases (more signal at an applied torque).

Particular at the electrical connections between the electrical supply cables and the "to be encoded" shaft 150 the results are very challenging. Even the slightest differences in impedance where the cable connects with the shaft (or tube surface) will cause that the electrical current will be not uniformly distributed around the shaft 150 at this particular area.

As the current is flowing further in the shaft 150, the electrical current density will become more and more uniformly around the shaft 150. If it would be possible to ensure that the electrical current enters uniformly around the shaft 150 right where the electrical wires are connected, then the useful sensing area will become larger (moves nearer to the point where the wires connect with the shaft 150).

The method of magnetizing the shaft according to the invention is exactly doing that: it forces the electrical current to flow most uniformly (in respect when monitoring the current flow density 360° around the shaft).

Thus, the invention has the benefits that it simplifies the way the electrical connections need to be made to the shaft 150. Further, the invention improves greatly several sensor performances. Moreover, the encoding equipment is simplified, and with this the manufacturing equipment costs are reduced.

Fig. 3C shows an alternative arrangement of an apparatus for magnetizing the shaft 150. In addition to the first and the second connections 201, 202, the hollow tube 121 further has a third electrical connection 351, and the solid shaft 150 has a third electrical connection 352. In the case of Fig. 3C, two different pulses I1 and I2 are applied to the array in the manner as shown in Fig. 3C. The first electrical signal I1 is applied between the first electrical connection 201 of the hollow tube 121 and the second electrical connection 204 of the solid shaft 150. A second electrical signal I2 is applied between the third electrical connection 351 of the hollow tube 121 and the third electrical connection 352 of the solid shaft 150.

Further, an electrically conductive coupling element 350 is provided to couple the second electrical connection 202 of the hollow tube 121 to the first electrical connection 203 of the solid shaft 150. The current distribution shown in Fig. 3C achieves a magnetic field distribution which yields a homogeneous current profile in elements 121, 150, thus achieving

a sensor with a well-defined magnetization, i.e. a well-defined magnetically encoded region 122.

Figs. 4A, 4B illustrate another embodiment of an apparatus for magnetizing a shaft 150 according to the invention,

Fig. 4A shows a configuration in which the coupling between the connection 202 of the hollow tube 121 and the connection 203 of the conductive solid shaft 150 are realized by a conductive based plate 400 as a coupling element.

Fig. 4B shows the apparatus of Fig. 4A in a state in which a current is applied. The current flows through the shaft 150, through the plate 400 and from there – in opposite direction compared to the flowing direction in the shaft 150 – through the tube 121. As can be seen in Fig. 4B, the current is applied to the tube 121 via a plurality of electrical connection cables which are arranged circumferentially along the perimeter of the upper circular surface of the tube 121. Such an arrangement with - for instance six or eight - cables yields a very homogeneous current distribution.

As an alternative to the provision of a conductive plate 400 for coupling the tube 121 to the shaft 150, the tube 121 can remain uncoupled from the shaft 150 (i.e. the plate 400 can be omitted), and two oppositely oriented current signals can be flown through the shaft 150 and through the tube 121, wherein the current in the shaft 150 may serve to magnetize the shaft 150, and the current in the tube 121 may serve to provide a counter magnetic field to increase the homogeneity of magnetizing the shaft 150. Thus, two signals are applied simultaneously, one to the tube 121 and the other one to the shaft 150.

In the following, referring to **Fig. 5**, an apparatus 500 for magnetizing a magnetizable tube 501 according to another embodiment of the invention will be described.

The apparatus 500 comprises the magnetizable tube 501, namely a hollow cylinder, a wire 502 having a first part 502a, a second part 502b and a third part 502c, wherein a current can flow through the wire 502. An electrical power source 503 is provided which can inject an electrical current in the wire 502 in an operation state in which a switch 504 is closed. Thus, by closing the switch 504, a pulse current 505 can be injected in wire 502. However, alternatively to the pulse current 505, a pulse as shown in Fig. 3D, for instance, can also be injected in the wire 502. Although a pulse as the one shown in Fig. 3D is preferred, any other appropriate pulse shape like the one shown in Fig. 5 can be injected in the wire 502.

The magnetizable tube 501 is made of industrial steel and has a wall thickness of 4 cm, a diameter of 88 cm and a length of several metres. The tube 501 to be magnetized is arranged in such a manner that the tube 501 encloses the first part 502a of the wire 502. The electrical power source 503 is adapted to apply a pulsed current 505 to the wire 502, wherein the pulsed current 505 is adapted such that the magnetizable tube 501 becomes magnetized. When such a current pulse 505 is applied to the first part 502a of the wire 502, a magnetic field is generated in the vicinity and around the first part 502a of the wire 502 which influences, similar like in the case of a transformator, the elementary magnets within the magnetizable tube 501. Consequently, the pulse 505 will cause the tube 501 to become magnetized.

As can be seen in Fig. 5, the first part 502a of the wire 502 is arranged at the centre of the hollow tube 501. In contrast to the configuration shown in Fig. 3A to 3D, the electrical power source 503 is connected to the wire 502, but is disconnected from the magnetizable tube 501. Further, a hollow shielding cylinder 506 is provided which is manufactured similarly to the magnetizable tube 501. As can be further seen, particularly the third part 502c of the wire 502 is free from an enclosure with the magnetizable tube 501, i.e. is not surrounded by the magnetizable tube 501. The shielding cylinder 506 is arranged and adapted to electromagnetically shield (i.e. decouple) the third part 502c of the wire 502 being free from

an enclosure with the magnetizable tube 501 from the magnetizable tube 501. The shielding tube 506 made of magnetizable material is arranged between the magnetizable tube 501 and the third part 502c of the wire 502. Thus, the current pulse 505 flowing through all parts 502a, 502b, 502c of the wire 502 acts on the magnetizable tube 501 essentially only at the first part 502a which is enclosed by the magnetizable tube 501, whereas the current flowing in a counter direction compared to the first part 502a through the third part 502c is avoided to negatively influence, particularly to weaken, the magnetization generated in the magnetizable tube 501.

Also the second part 502b of the wire 502 can be shielded from the magnetizable tube 501 by a similar shielding element like the shielding cylinder 506.

Fig. 6A shows a schematic top view of the apparatus 500. As can be seen, the shielding cylinder 506 efficiently shields the third part 502c of the wire 502 from the tube 501.

Figs. 6B to **6D** show further embodiments of shielding elements.

Fig. 6B shows a configuration in which four shielding cylinders 600 to 603 are arranged around the third part 502c of the wire 502. Thus, the shielding cylinders 600 to 603 made of magnetizable material are arranged surrounding the portion 502c of the wire 502 which is free from an enclosure with the magnetizable tube 501.

Fig. 6C shows a plurality of cylindrical shafts 610 to 617 which are arranged around the third part 502c of the wire 502 to shield the third part 502 being free of an enclosure with the magnetizable tube 501 from the magnetizable tube 501.

Fig. 6D shows a six tubes 620 to 625 which are arranged to surround the third part 502c.

In the following, referring to **Fig. 7**, an apparatus 700 for magnetizing a magnetizable tube 501 according to another embodiment of the invention will be described.

According to the embodiment of Fig. 7, the shielding cylinder 506 is arranged to surround the third part 502c of the wire 502. Further, the electrical signal source 503 is realized as a bank of (charged) capacitors 701 which may be discharged by closing the switch 504 to generate a pulse as the one shown in Fig. 3D. The magnetizing apparatus 700 is "mobile" which is illustrated by means of a vehicle 702 which transports the capacitor banks 701 to a place at which a magnetizable tube 501 (i.e. drilling equipment at a mining place) shall be magnetized.

Thus, the mobile processing unit of Fig. 7 can be brought closest to drilling or large tooling shafts.

In the following, referring to **Fig. 8A** and **Fig. 8B**, an apparatus 800 for calibrating a force and torque sensor device 810 will be described.

The apparatus 800 comprises the force and torque sensor device 810, a pre-known mass 811 with a weight of 1000 kg and a calibrating unit 818.

The force and torque sensor device 810 has a magnetically encoded region 812 on a hollow tube 813 and four magnetic field detecting coils 814 to 817.

The pre-known weight 811 is put on the top of the force and torque sensor device 810 to apply a pre-known axial force to the magnetized hollow tube 813. The calibrating unit 818 which is connected to the magnetic field detecting coils 814 to 817 is adapted to calibrate the force and torque sensor 810 based on a correlation between the pre-known mass 811 and a detecting signal resulting from the pre-known force of the mass 811.

Thus, a pre-known mass 811 is applied on the top of the horizontally arranged hollow tube 813 which stands on a horizontal and stable base 819. As a consequence of the mass 811 applied to the top of the force and torque sensor device 810 (which may be magnetized in a manner as shown in Fig. 7), the magnetic field generated by the magnetically encoded region 812 changes so that a signal in the magnetic field detecting coils 814 to 817 occurs. Thus, this signal which is processed in the calibration unit 818 is correlated to the pre-known axial force applied to the magnetized tube 813 by the known mass 811. This pair of data pairs, namely the known axial force and the detected signal, can be stored in the calibration unit 818.

The upper surface of the hollow tube 813 (onto which the mass 811 is put) is preferably arranged horizontally so that the vector of the force generated by the mass 811 on the top of the tube 813 is oriented essentially perpendicular to the surface of the hollow tube 813 (or is directed towards the center of the earth). In case that the upper surface of the tube 813 and/or the base 819 is/are not oriented in a horizontal manner, an angular correction calculation may be necessary or desirable.

When the drilling shaft 813 is brought back in the ground and is used for drilling, axial forces and torque applied to the drilling shaft 813 can be measured by the magnetic field detecting coils 814 to 817 and may be compared to the calibration signal. Thus, an absolute measurement of torque and force can be carried out based on a calibration with an axial load 811.

For the calibration, the coils 814 to 817 have to be arranged such that an axial force can be measured. For the torque sensing operation, the coils 814 to 817 have to be arranged such that torque can be measured. Thus, the axes of the coils 814 to 817 may have to be re-oriented, accordingly, when switching from a calibration mode to a measuring mode.

Figs. 9A and **9B** show two possible configurations for arranging the magnetic field detecting coils 814 to 817.

Fig. 10 shows three possible configurations of drilling shafts 1000 having magnetically encoded regions 1001, 1002 or 1003.

The markings 1001 to 1003 symbolize where the drilling shaft 1000 (or rotational power transmitting shaft 1000) have magnetically encoded regions. In real life, the encoding 1001 to 1003 is optically invisible and does not change or interfere with any of the mechanical properties of the shaft 1000. The drilling shaft 1000 can be encoded at a specific location 1001, or at a section 1002, or in its entirety 1003. In many cases, the encoding at a specific location 1001 is advisable for a static system operation only. The encoding options 1002, 1003 are particularly dedicated for applications where the drilling shaft 1000 is rotating or in motion in some ways.

Fig. 11 shows two configurations how magnetic field detecting coils 1100 to 1103 may be arranged around the drilling shaft 1000.

In the following, the so-called PCME ("Pulse-Current-Modulated Encoding") Sensing Technology will be described in detail, which can, according to a preferred embodiment of the invention, be implemented to magnetize a magnetizable object which is then partially demagnetized according to the invention. In the following, the PCME technology will partly described in the context of torque sensing. However, this concept may implemented in the context of position sensing as well.

In this description, there are a number of acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many terms that are particularly related to the

magnetostriction based NCT sensing technology. It should be noted that in this description, when there is a reference to NCT technology or to PCME, it is referred to exemplary embodiments of the present invention.

Table 1 shows a list of abbreviations used in the following description of the PCME technology.

Acronym	Description	Category
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Table 1: List of abbreviations

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

In the following, a magnetostriction principle based Non-Contact-Torque (NCT) Sensing Technology is described that offers to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology

is called: PCME (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

In the following, a Magnetic Field Structure (Sensor Principle) will be described.

The sensor life-time depends on a "closed-loop" magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress or motion stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

Fig.12 shows that two magnetic fields are stored in the shaft and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.

Fig.13 illustrates that the PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like reciprocation motion or torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

As illustrated in **Fig.14**, when no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical stresses are applied the magnetic flux lines tilt in proportion to the applied stress (like linear motion or torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

The benefits of such a magnetic structure are:

- ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- ☐ Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- ☐ This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST

Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.

Referring to **Fig.15**, when torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.

Referring to **Fig.16**, an exaggerated presentation is shown of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

In the following, features and benefits of the PCM-Encoding (PCME) Process will be described.

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance sensing features like:

- ☐ No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- ☐ Nothing has to be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- ☐ During measurement the SH can rotate, reciprocate or move at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)

- ☐ High measurement repeatability
- ☐ Very high signal resolution (better than 14 bit)
- ☐ Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (Uniqueness of this technology):

- ☐ More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- ☐ Easy and simple shaft loading process (high manufacturing through-putt).
- ☐ No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- ☐ Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- ☐ Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- ☐ Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- ☐ The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).

- Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- Sensitive to mechanical forces in all three dimensional axis.

In the following, the Magnetic Flux Distribution in the SH will be described.

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early experiments that used DC currents failed because of luck of understanding how small amounts and large amounts of DC electrical current are travelling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").

Referring to **Fig.17**, an assumed electrical current density in a conductor is illustrated.

It is widely assumed that the electrical current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electrical current (DC) passes through the conductor.

Referring to **Fig.18**, a small electrical current forming magnetic field that ties current path in a conductor is shown.

It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the centre of the conductor. The two main reasons for this are: The electrical current passing through a conductor generates a magnetic

field that is tying together the current path in the centre of the conductor, and the impedance is the lowest in the centre of the conductor.

Referring to **Fig.19**, a typical flow of small electrical currents in a conductor is illustrated.

In reality, however, the electrical current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electrical lightening in the sky).

At a certain level of electrical current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electrical current is flowing near or at the centre of the SH, the permanently stored magnetic field will reside at the same location: near or at the centre of the SH. When now applying mechanical torque or linear force for oscillation/reciprocation to the shaft, then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.

Referring to **Fig.20**, a uniform current density in a conductor at saturation level is shown.

Only at the saturation level is the electrical current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.

Referring to **Fig.21**, electrical current travelling beneath or at the surface of the conductor (Skin-Effect) is shown.

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location / position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the centre of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the centre of the shaft at very low AC frequencies (as there is more space available for the current to flow through).

Referring to **Fig.22**, the electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies is illustrated.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).

Again referring to **Fig.13**, a desired magnetic sensor structure is shown: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the centre of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has

a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.

Referring to **Fig.23**, magnetic field structures stored near the shaft surface and stored near the centre of the shaft are illustrated.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is travelling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the "permanent" magnet encoding.

A much simpler and faster encoding process uses "only" electrical current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.

Referring to **Fig.24**, the magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them are shown.

The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is cancelling out the measurable effects in the inner halve of the "U".

Referring to **Fig.25**, the zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have cancelled-out each other (G).

Referring to **Fig.26**, the zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

In the following, an Encoding Pulse Design will be described.

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

In the following, a Rectangle Current Pulse Shape will be described.

Referring to **Fig.27**, a rectangle shaped electrical current pulse is illustrated.

A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.

Referring to **Fig.28**, a relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope is shown.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electrical current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

Referring to **Fig.29**, increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession is shown.

The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

In the following, a Discharge Current Pulse Shape is described.

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

As shown in **Fig.30,** a sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.

Referring to **Fig.31,** a PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current is illustrated.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.

Referring to **Fig.32,** Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse is illustrated.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).

Referring to **Fig.33,** Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels is shown.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.

Referring to **Fig.34,** better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

Referring to **Fig.35,** flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

In the following, Electrical Connection Devices in the frame of Primary Sensor Processing will be described.

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I).

Referring to **Fig.36**, a simple electrical multi-point connection to the shaft surface is illustrated.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

Referring to **Fig.37**, a multi channel, electrical connecting fixture, with spring loaded contact points is illustrated.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.

Referring to **Fig.38**, it is illustrated that increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.

Referring to **Fig.39**, an example of how to open the SPHC for easy shaft loading is shown.

In the following, an encoding scheme in the frame of Primary Sensor Processing will be described.

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electrical currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electrical current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.

Referring to **Fig.40**, two SPHCs (Shaft Processing Holding Clamps) are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I)

will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

Referring to **Fig.41**, a Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows cancelling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the centre of the final Primary Sensor Region the Centre SPHC (C-SPHC), and the SPHC that is located at the left side of the Centre SPHC: L-SPHC.

Referring to **Fig.42**, the second process step of the sequential Dual Field encoding will use the SPHC that is located in the centre of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the centre SPHC, called R-SPHC.

Important is that the current flow direction in the centre SPHC (C-SPHC) is identical at both process steps.

Referring to **Fig.43,** the performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used centre SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.

Fig.44 shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.

Referring to **Fig.45,** magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design are shown when no torque or linear motion stress is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.

Referring to **Fig.46,** when torque forces or linear stress forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines, as shown.

Referring to **Fig.47**, when the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

In the following, a Multi Channel Current Driver for Shaft Processing will be described.

In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electrical current controlled driver stages can be used to overcome this problem.

Referring to **Fig.48**, a six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH) is shown. As the shaft diameter increases so will the number of current driver channels.

In the following, Bras Ring Contacts and Symmetrical "Spot" Contacts will be described.

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

Referring to **Fig.49**, bras-rings (or Copper-rings) tightly fitted to the shaft surface may be used, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

In the following, a Hot-Spotting concept will be described.

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.

Referring to **Fig.50**, a PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).

Referring to **Fig.51**, a PCME processed Sensing region with two "Pinning Field Regions" is shown, one on each side of the Sensing Region.

By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed

simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.

Referring to **Fig.52**, a parallel processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region is illustrated, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor centre region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

Referring to **Fig.53**, a Dual Field (DF) PCME sensor with Pinning Regions either side is shown.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

In the following, the Rotational Signal Uniformity (RSU) will be explained.

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.

Referring to **Fig.54**, when the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.

Referring to **Fig.55**, by widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Next, the basic design issues of a NCT sensor system will be described.

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

In case a stand-alone torque sensor device or position detecting sensor device will be applied to a motor-transmission system it may require that the entire system need to undergo a major design change.

In the following, referring to Fig.56, a possible location of a PCME sensor at the shaft of an engine is illustrated.

Next, Sensor Components will be explained.

A non-contact magnetostriction sensor (NCT-Sensor), as shown in **Fig.57**, may consist, according to an exemplary embodiment of the present invention, of three main functional elements: The Primary Sensor, the Secondary Sensor, and the Signal Conditioning & Signal Processing (SCSP) electronics.

Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the individual components to build the sensor system under his own management, or can subcontract the production of the individual modules.

Fig.58 shows a schematic illustration of components of a non-contact torque sensing device. However, these components can also be implemented in a non-contact position sensing device.

In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".

In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact sensor:

- ☐ ICs (surface mount packaged, Application-Specific Electronic Circuits)
- ☐ MFS-Coils (as part of the Secondary Sensor)
- ☐ Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.

Fig.59 shows components of a sensing device.

As can be seen from **Fig.60**, the number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.

In the following, a control and/or evaluation circuitry will be explained.

The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits,

the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present invention) offers a number of different application specific circuits:

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- ☐ Optional Fault Detection Circuit

Fig.61 shows a single channel, low cost sensor electronics solution.

Fig.62 shows a dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Next, the Secondary Sensor Unit will be explained.

The Secondary Sensor may, according to one embodiment shown in **Fig.63**, consist of the elements: One to eight MFS (Magnetic Field Sensor) Coils, the Alignment- & Connection-Plate, the wire harness with connector, and the Secondary-Sensor-Housing.

The MFS-coils may be mounted onto the Alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSUs operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSUs and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

In the following, Secondary Sensor Unit Manufacturing Options will be described.

When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may be done under the customer's management.
- ☐ only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

Fig.64 illustrates an exemplary embodiment of a Secondary Sensor Unit Assembly.

Next, a Primary Sensor Design is explained.

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.

Fig.65 illustrates two configurations of the geometrical arrangement of Primary Sensor and Secondary Sensor.

Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding

Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances, the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.

As illustrated in **Fig.66**, the spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

Next, the Primary Sensor Encoding Equipment will be described.

An example is shown in **Fig.67**.

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, ...) and so does the processing equipment required. Some of the available magnetostriction sensing technologies do not need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).

While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

One should be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)
- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

In the following, referring to **Fig. 68**, an apparatus 6800 for magnetizing an object will be explained.

As shown in Fig.68, the shaft 150 enclosed by the hollow tube 121 can be magnetized by applying an electrical signal generated by the electrical power source 503 to the hollow tube 121. The apparatus 6800 allows magnetizing the shaft 150 by arranging the hollow tube 121 in such a manner that the hollow tube 121 encloses the shaft 150, and by applying an electrical signal via a plurality of circumferentially arranged contacts to the hollow tube 121. The electrical signal generated by the electrical power source 503 is preferably a pulsed signal such that at least a portion of the shaft 150 is magnetized. As shown in Fig. 68, two end portions of the shaft 150 outside the hollow tube 121 are short-circuited by a wire 6801 located outside the hollow tube 121.

Fig. 69 illustrates still another apparatus 6900 for magnetizing an object according to an embodiment of the invention.

The function of the apparatus 6900 is very similar to the function of the apparatus shown in Fig. 4A, Fig. 4B with the difference that the electrically conductive plate 400 is substituted by an electrically conductive fluid 6902 (e.g. mercury) which serves to electrically contact the shaft 150 to the hollow tube 121.

In the following, it is described how the apparatus 6900 is operated. A (for instance electrically insulating) spacer element 6901 in the form of a hollow cylinder with an inside diameter which essentially equals to the diameter of the shaft 150 and with an outside diameter which essentially equals to the inside diameter of the hollow tube 121 is arranged to seal and space the volume between the hollow tube 121 and the shaft 150 located within the hollow tube. Subsequently, the electrically conductive fluid 6902 is injected in the array 6900 to fill the space delimited by the hollow tube 121 and the shaft 150 and the spacer element 6901 to electrically couple the hollow tube 121 and the shaft 150 in a very flexible manner.

In the following, referring to **Fig. 70**, an apparatus 7000 for calibrating a force and torque sensor device according to the invention will be explained.

The apparatus 7000 comprises a base 7001 for receiving a shaft 7002 of a torque sensing device. The torque sensing device further includes two magnetic field detection coils 7004 and a magnetically encoded region 7003 which may be formed, for instance, by the above-described PCME technology. The base 7001 receives the shaft 7002 in such a manner that the shaft cannot be moved or rotated by an applied force. A motor 7005 is adapted to drive a rotatable element 7006 (e.g. a flywheel) which in term can rotate in a controllable manner and which is coupled to the shaft 7002 such that a mechanical impulse of the rotatable element 7006 can be transferred to the shaft 7002 to apply a (reactive) torque to the shaft 7002. As a response to such a calibrating torque of a known value, a signal can be detected by the coils 7004 which can serve for a calibration of the torque sensing device. Thus, the apparatus 7000

has the driven rotatable element 7006 as a pre-known torque generating element. Particularly, a sudden change of the rotation state of the rotatable element 7006 (e.g. a sudden brake signal) is useful as a source of (reactive) torque applied as a calibrating signal to the torque sensing device.

It should be noted that the term “comprising” does not exclude other elements or steps and the “a” or “an” does not exclude a plurality. Also elements described in association with different embodiments may be combined.

What Is claimed is:

1. A method for magnetizing a first object and/or a second object, the method comprising the steps of

arranging a first object in such a manner that the first object encloses a second object;

applying a first electrical signal to the second object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized;

wherein the first electrical signal is a first pulse signal;

wherein, in a time versus current diagram, the first pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge;

wherein the first electrical signal is a current or a voltage;

wherein a second electrical signal is applied to the second object after having applied the first electrical signal, wherein the second electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized, and wherein the second electrical signal differs from the first electrical signal concerning at least one of the group consisting of amplitude, sign, signal shape and duration;

wherein the second electrical signal is a second pulse signal;

wherein, in a time versus current diagram, the second pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge;

wherein the first object and/or the second object is magnetized by applying the first electrical signal and the second electrical signal such that in a direction essentially perpendicular to a surface of the first object and/or of the second object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction;

wherein the second electrical signal is a current or a voltage.

Abstract

A method and an apparatus for magnetizing an object, a method and an apparatus for calibrating a force and torque sensor device, a use of an apparatus for magnetizing an object in particular fields, and a use of an apparatus for calibrating a force and torque sensor device in particular fields

A method for magnetizing a first object and/or a second object comprises the steps of arranging a first object in such a manner that the first object encloses a second object, and applying a first electrical signal to the second object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized.

(Fig.4B)

Fig 1A

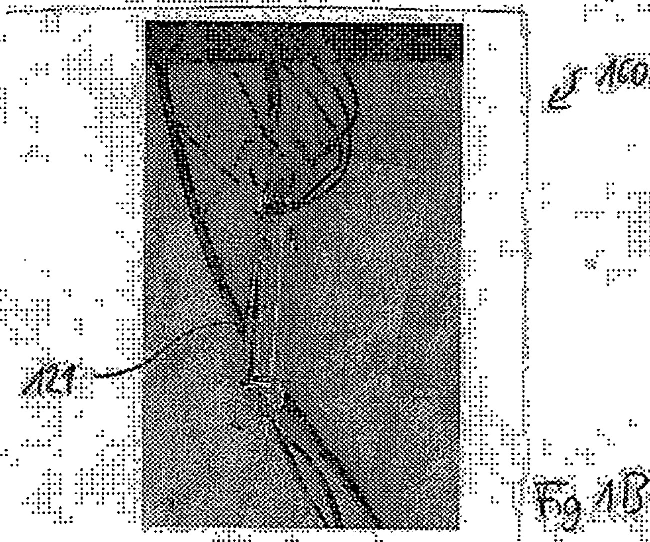


Fig 1B

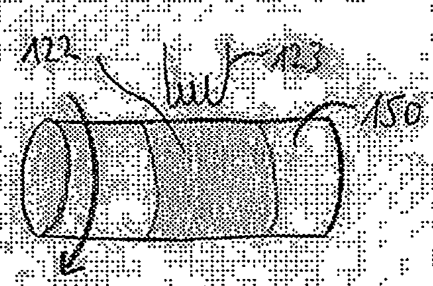
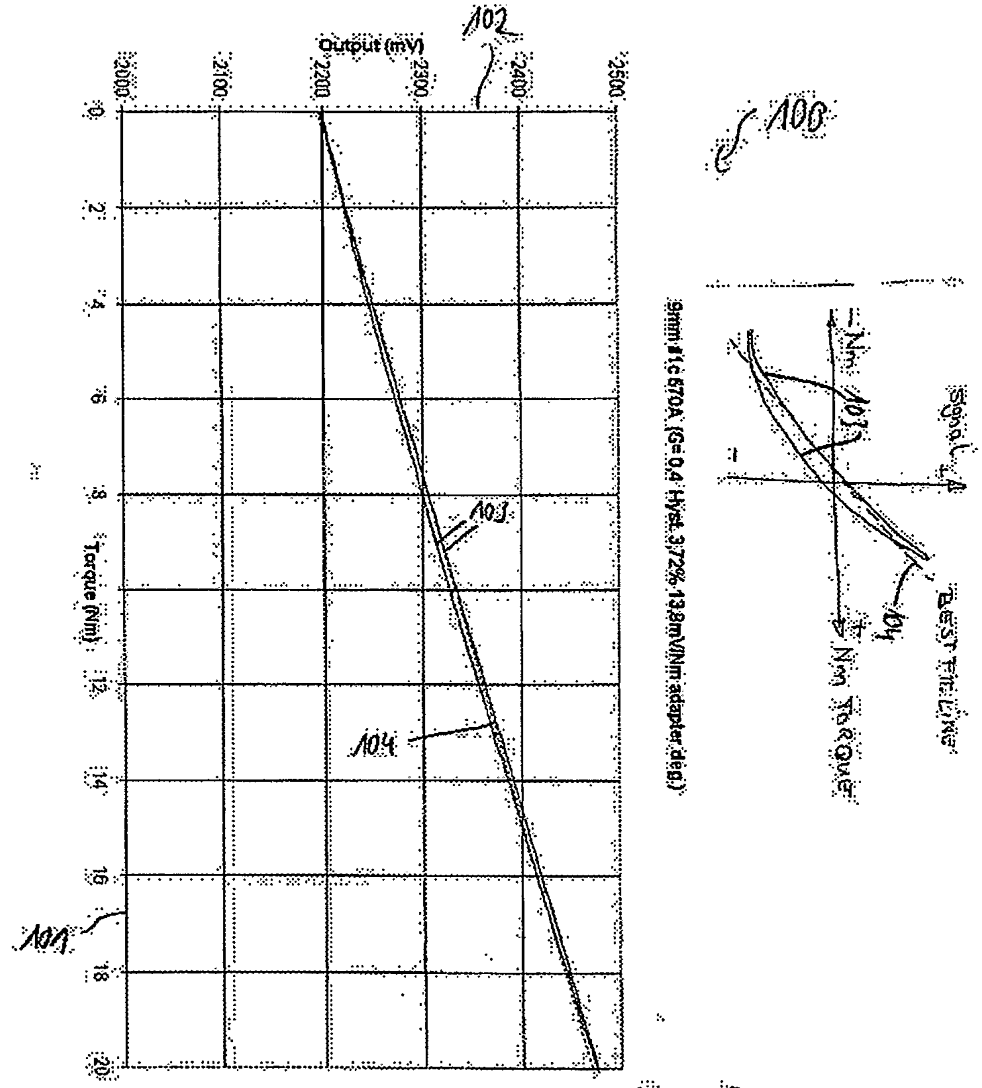


Fig 1C



Output (mV)
2000
2100
2200
2300
2400
2500
Torque (Nm)
102
103
104
101
100
Signal
Nm
Nm TORQUE
BEST FIT LINE

Fig 1D

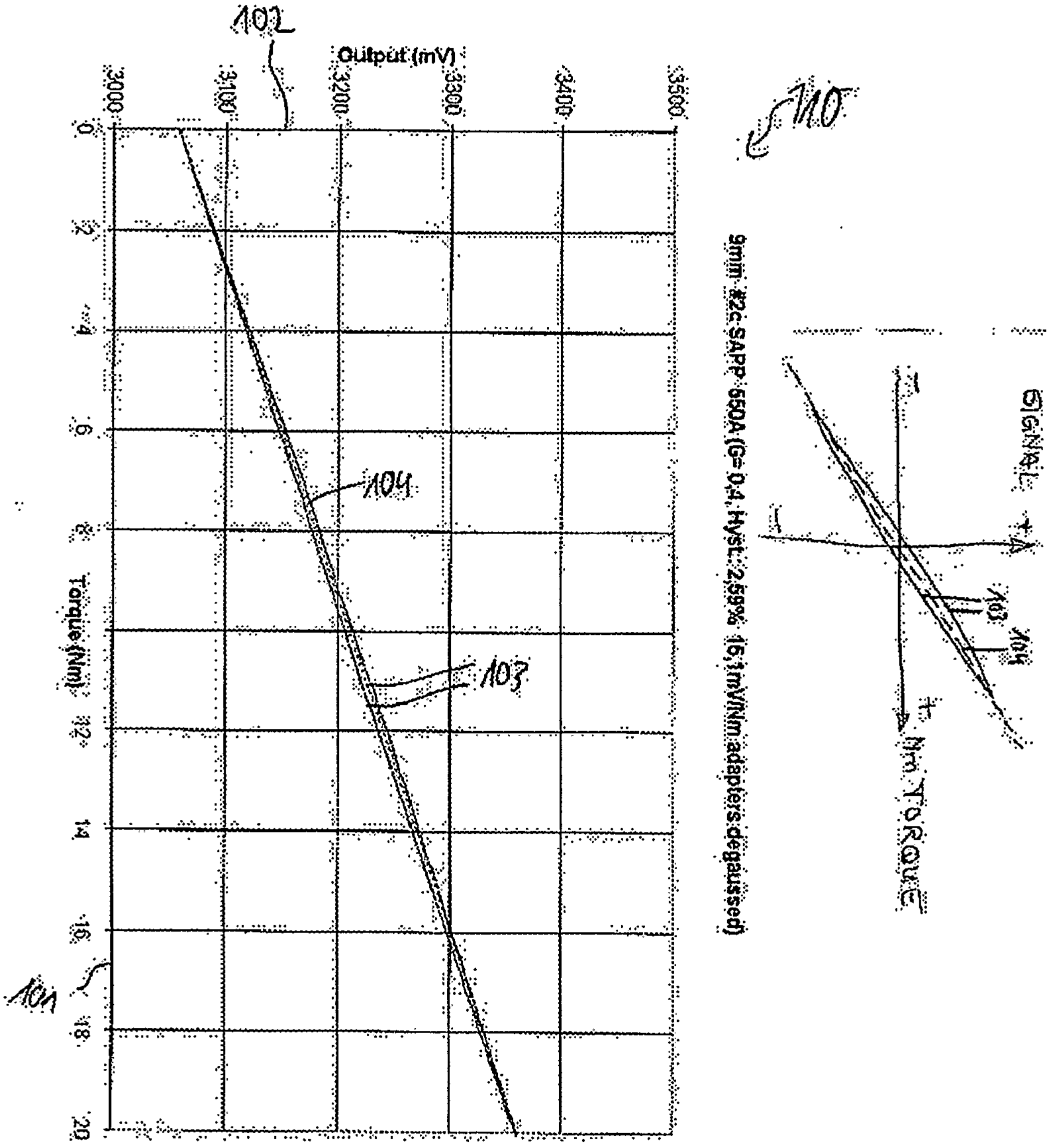

Output (mV)
3000
3100
3200
3300
3400
3500
Torque (Nm)
0
2
4
6
8
12
14
16
18
20
102
104
103
101
110
9mm #2c SAPP 650A (G=0.4, Hyst. 2.59% (5.1mV/Nm adapters degaussed)
SIGNAL
TORQUE
Nm

Fig. 1E

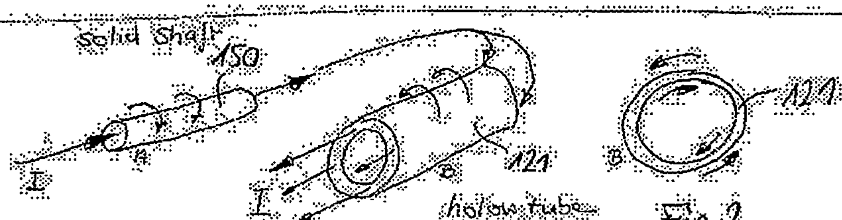


Fig 2

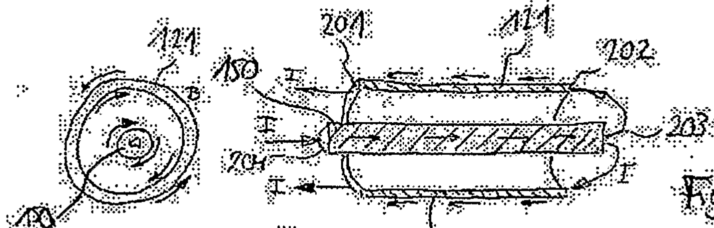


Fig 3A

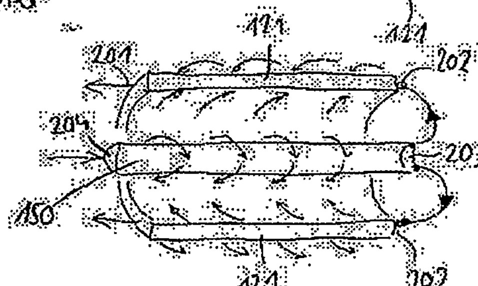


Fig 3B

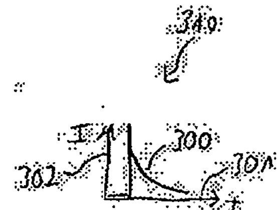


Fig 3D

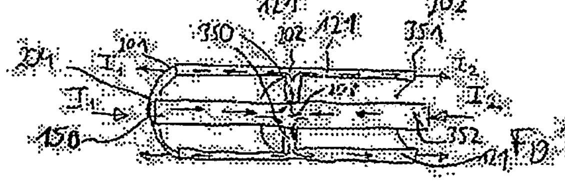


Fig 3C

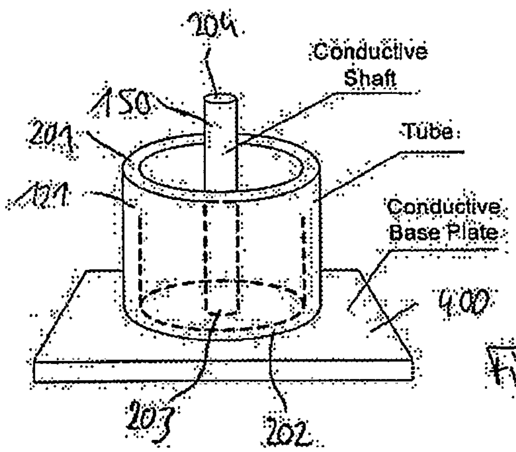

204
Conductive
Shaft
150
201
Tube
121
Conductive
Base Plate
400
203
202

Fig. 4A

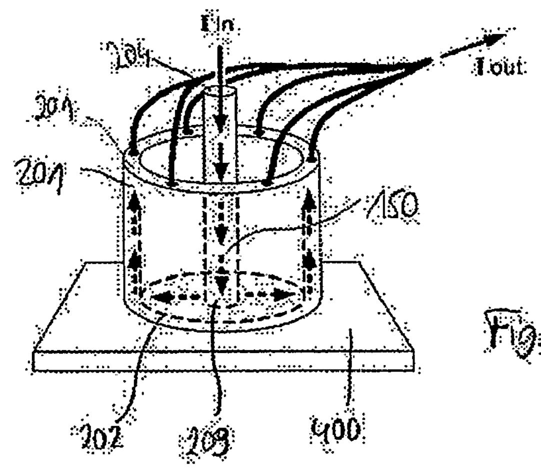

I in
204
I out
201
201
150
202
203
400

Fig. 4B

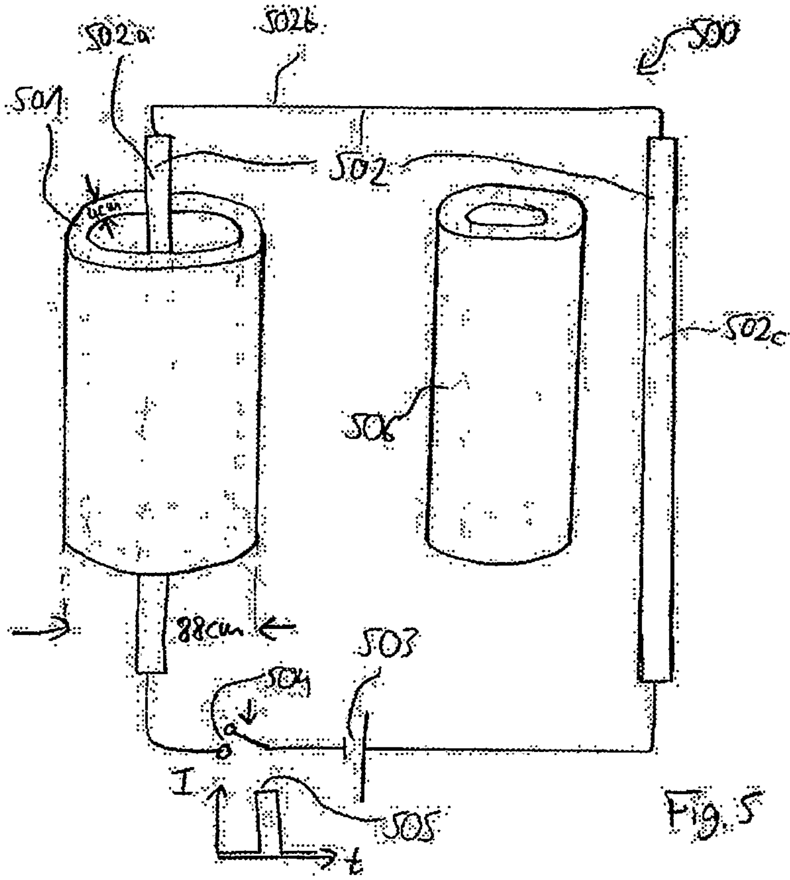

502a
502b
500
501
4cm
502
502c
506
88cm
503
504
I
505
t

Fig. 5

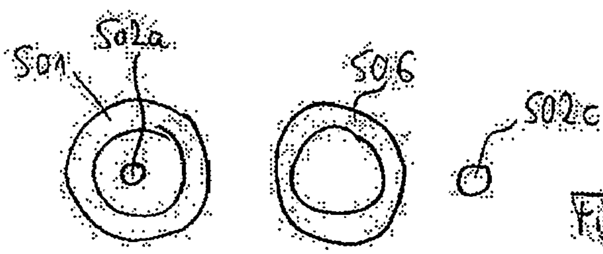

501
502a
506
502c

Fig. 6A

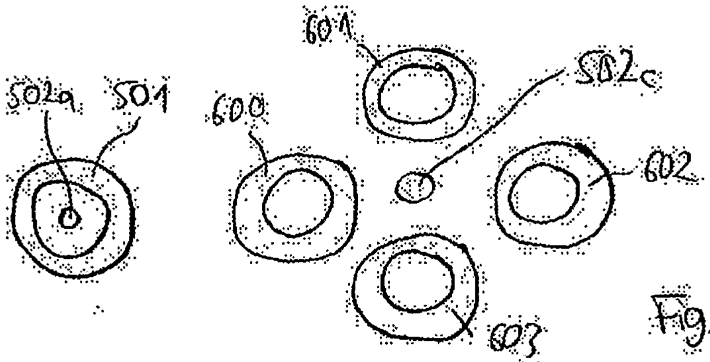


Fig. 6B

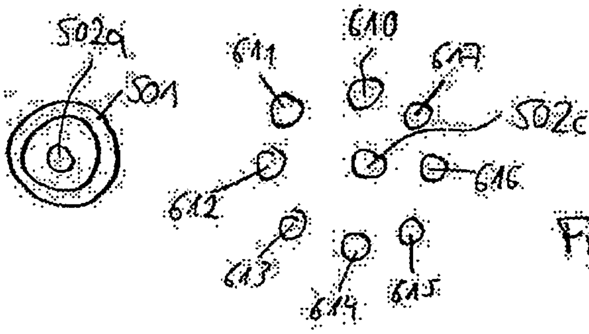


Fig. 6C

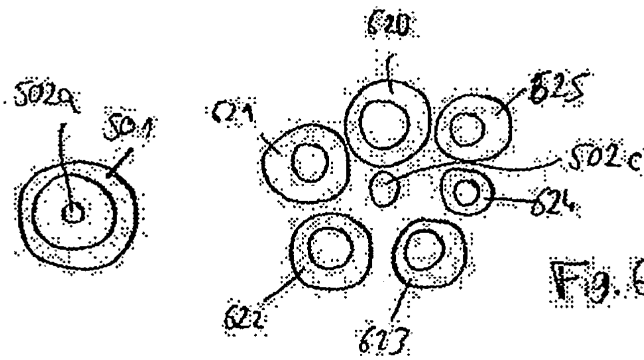


Fig. 6D

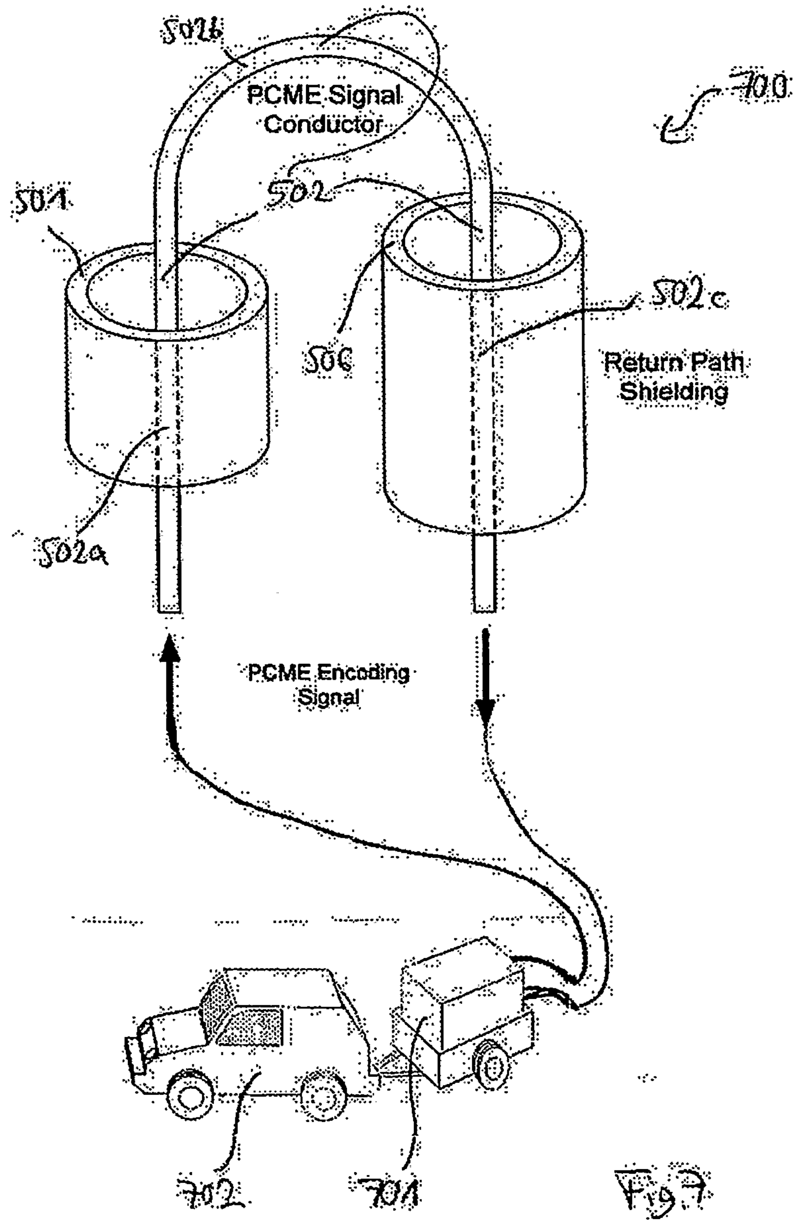

502b
PCME Signal
Conductor
700
501
502
502c
506
Return Path
Shielding
502a
PCME Encoding
Signal
702
701

Fig.7

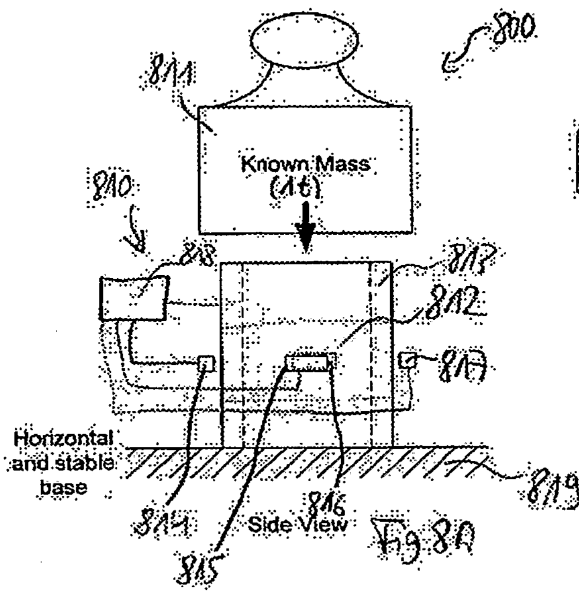


Fig.8A

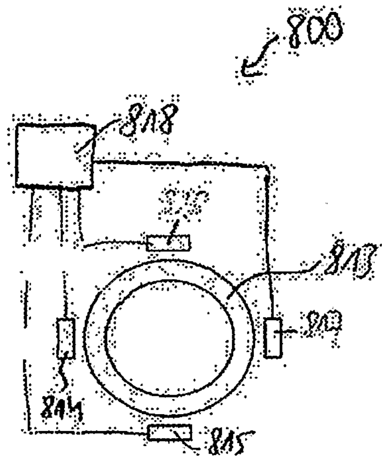


Fig.8B

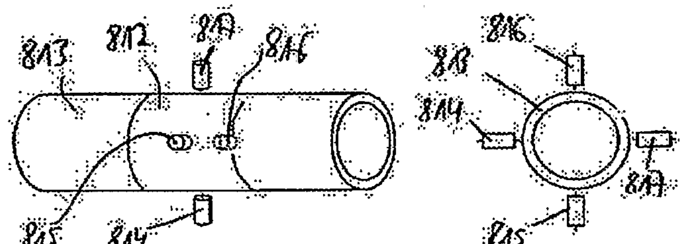


Fig.9A

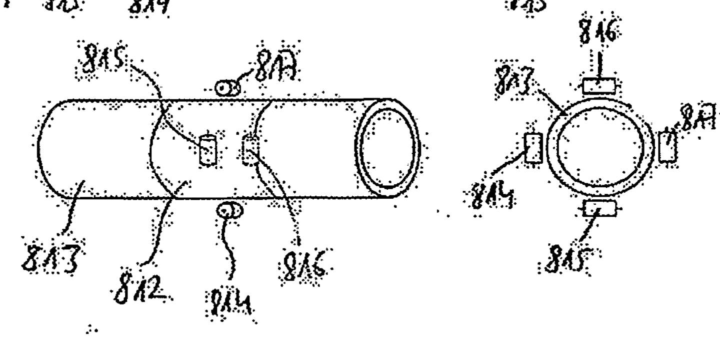


Fig.9B

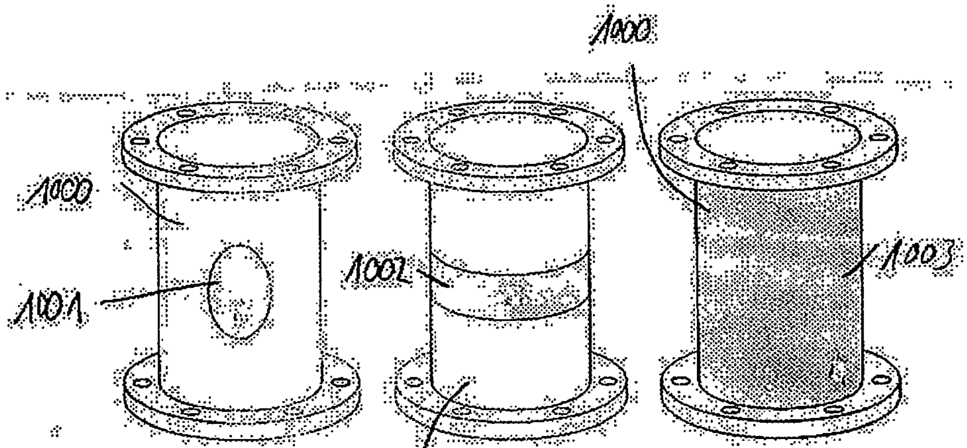

1000
1000
1001
1002
1003
1000

Fig. 10

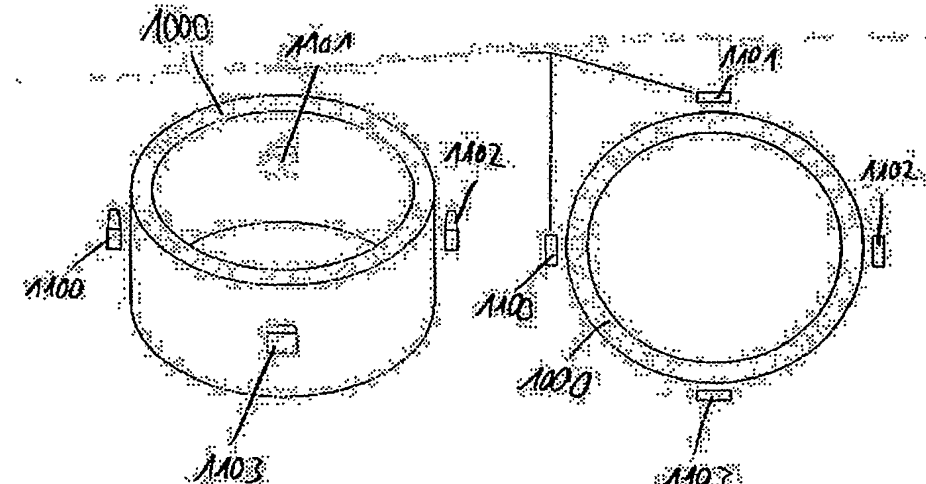

1000
1101
1101
1102
1102
1100
1100
1000
1103
1103

Fig. 11

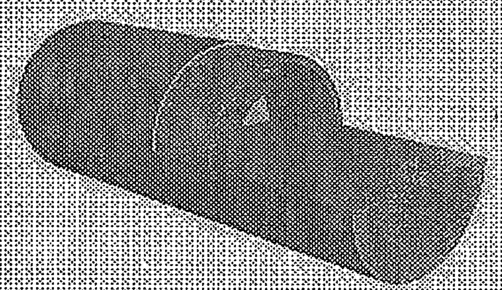


Fig 12

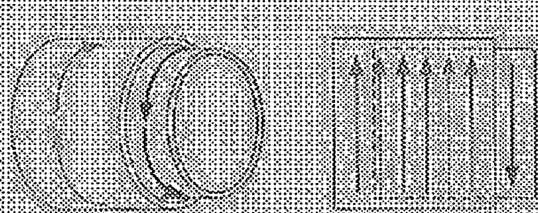


Fig 13

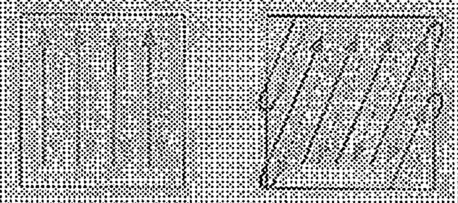


Fig 14

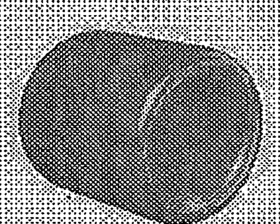


Fig 15

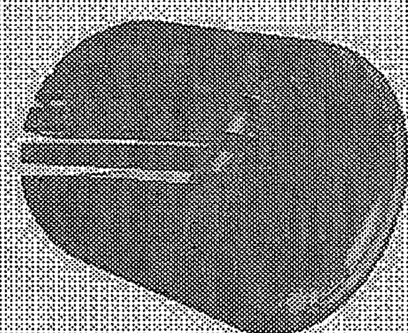


Fig 16

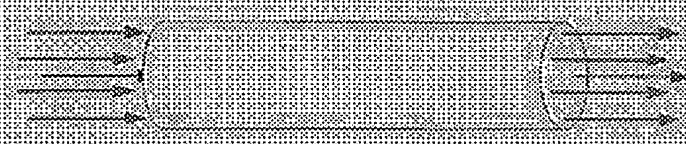


Fig. 17

Fig. 18

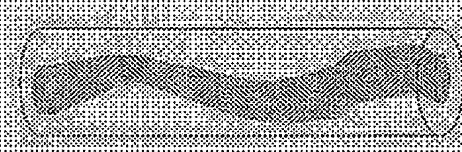


Fig. 19

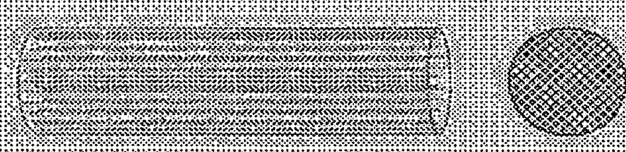


Fig. 20

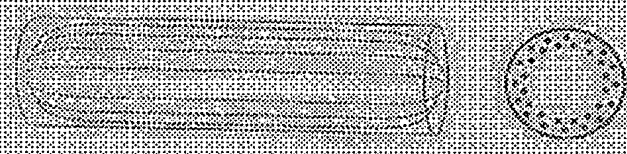


Fig 21

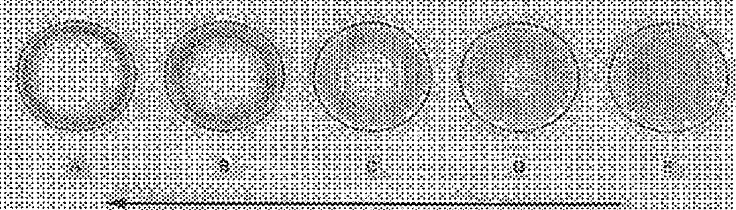


Fig 22

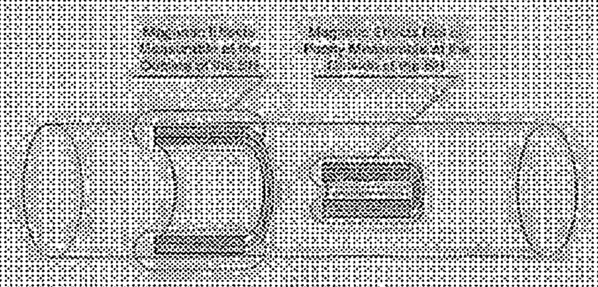


Fig 23

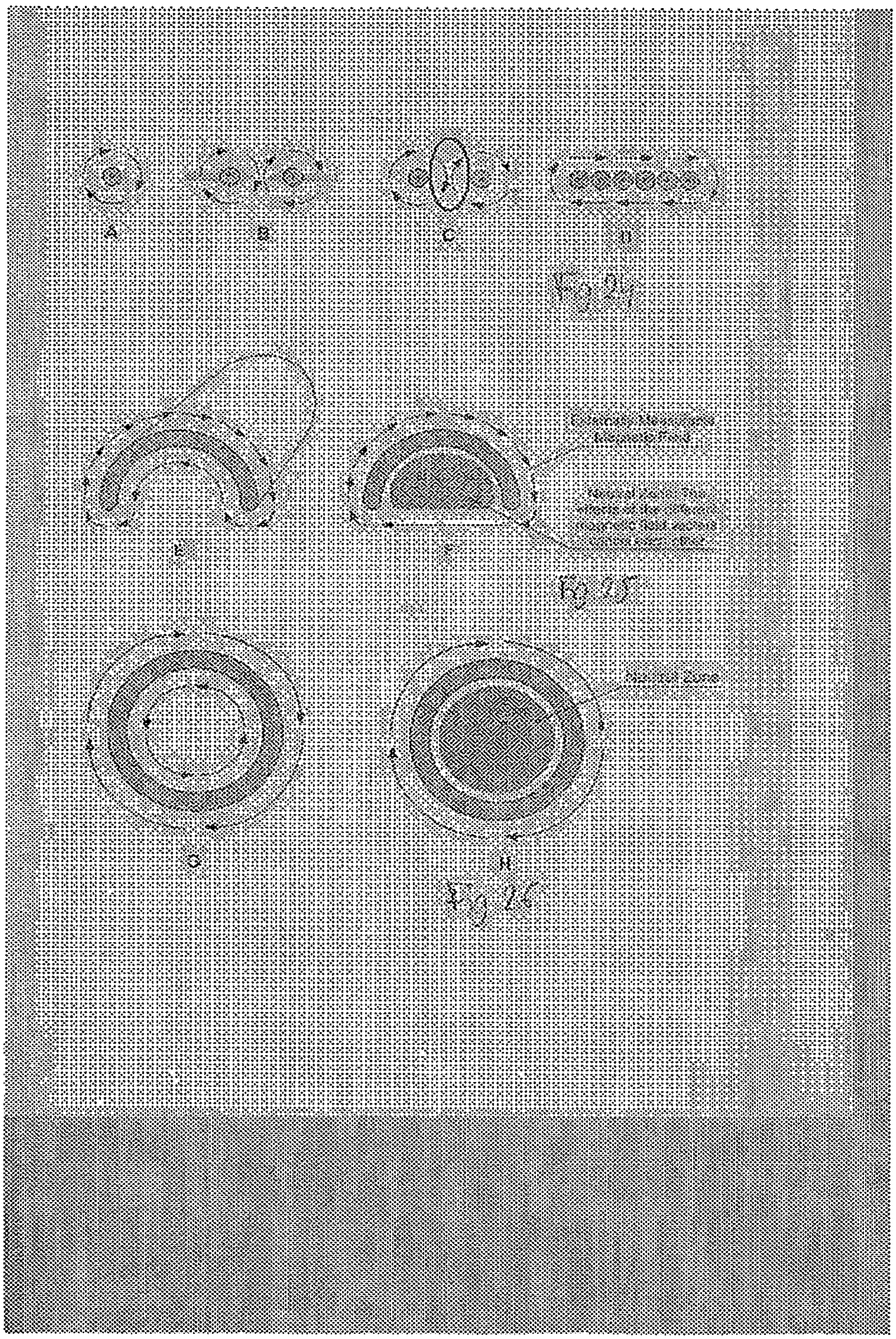


Fig 24

Fig 25

Fig 26

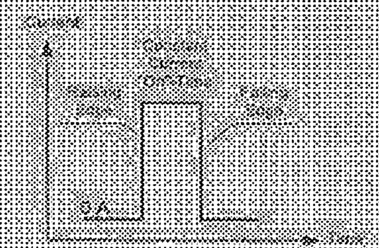


Fig 27

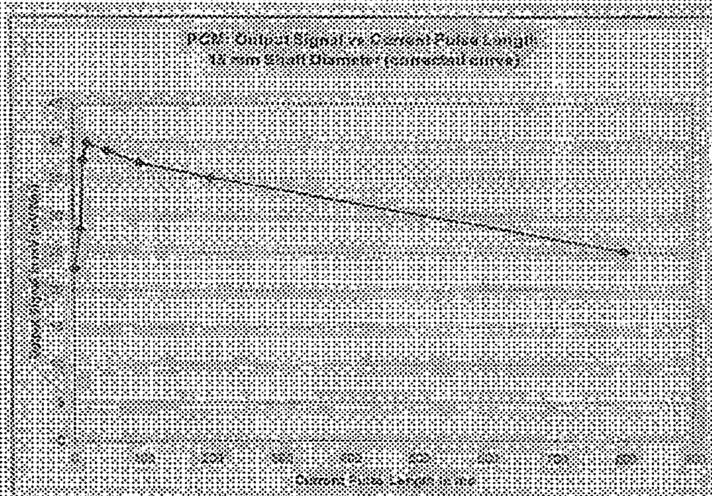


Fig 28

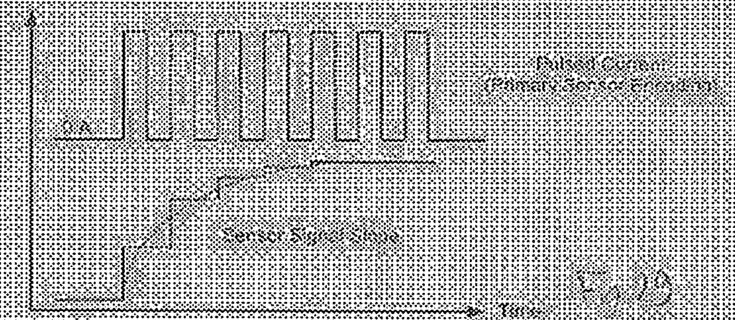


Fig 29

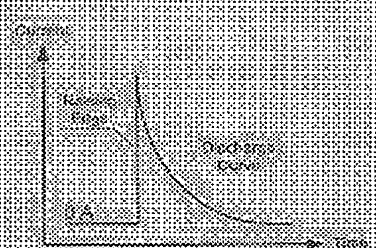


Fig 30

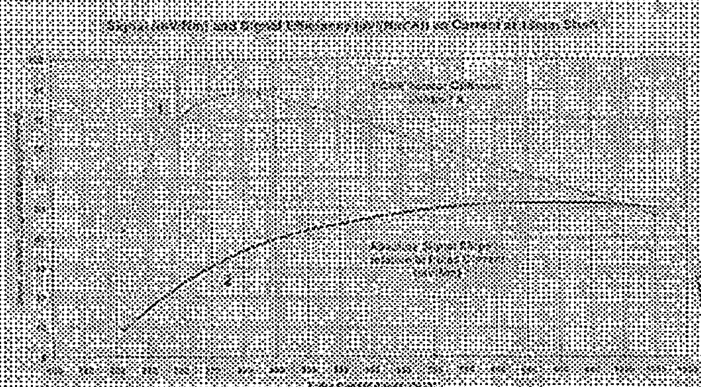


Fig 31

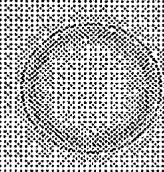


Fig 32

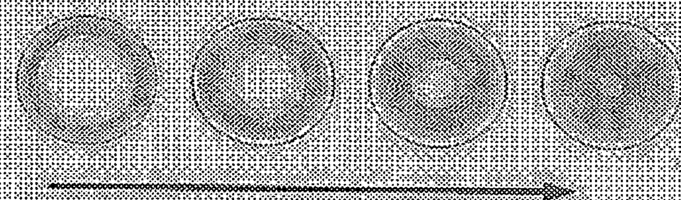


Fig 33

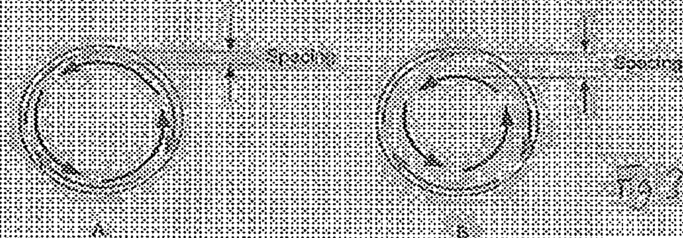


Fig 34

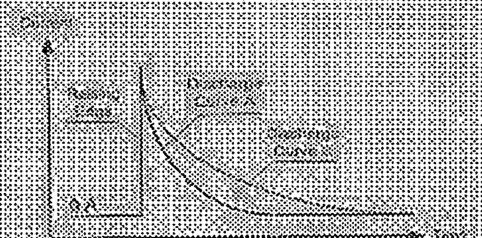


Fig 35

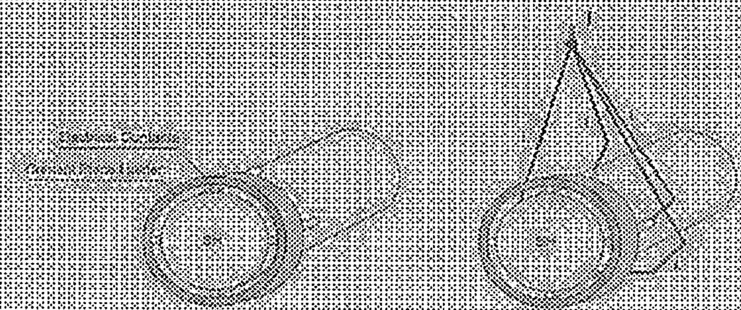


Fig 36

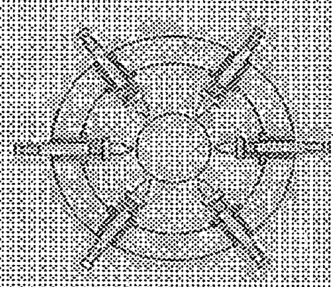


Fig 37

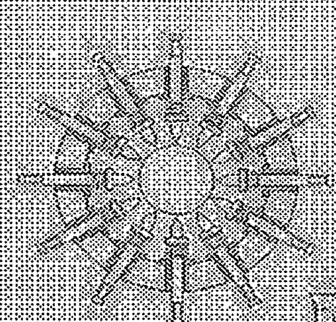


Fig 38

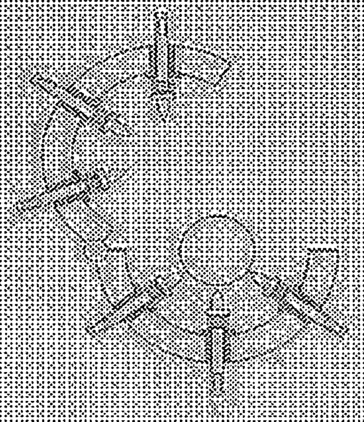


Fig 39

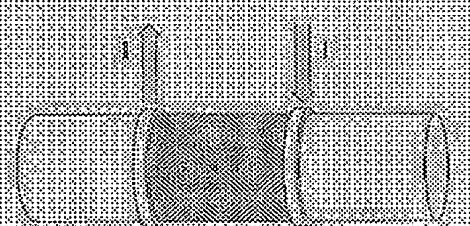


Fig 40

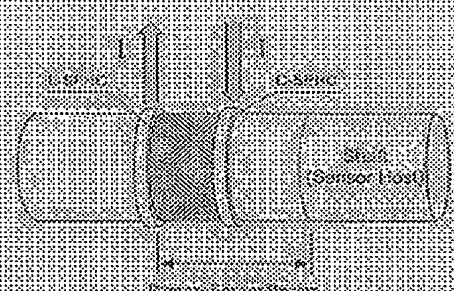


Fig 41

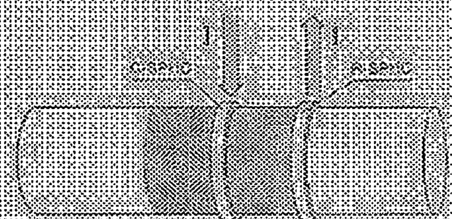


Fig 42

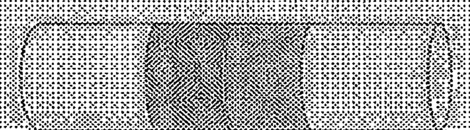


Fig 43

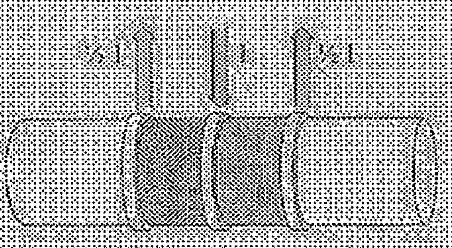


Fig 44

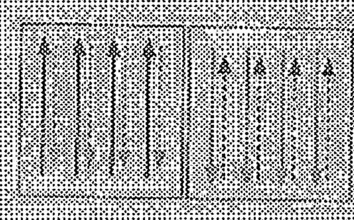


Fig 4B

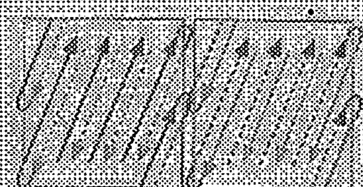


Fig 4C

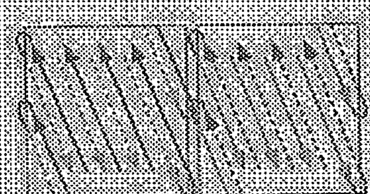
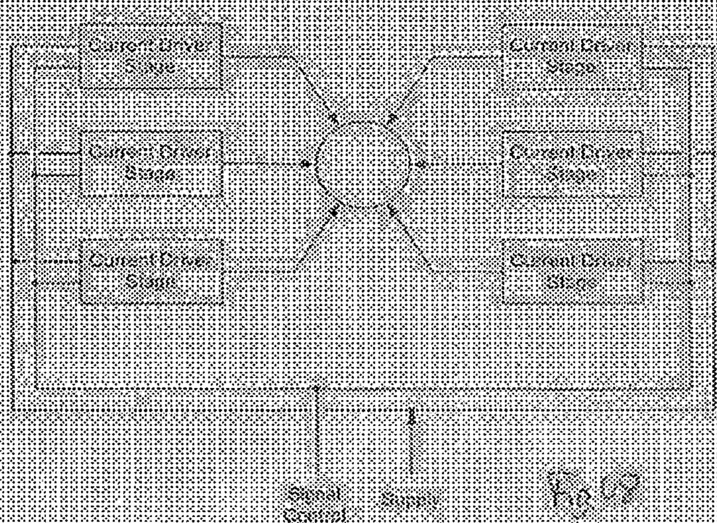


Fig 4D



Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Signal Control
Supply

Fig 48

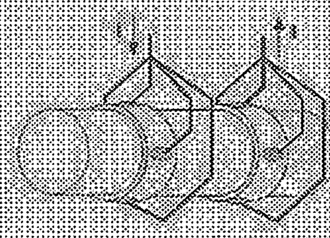


Fig 49

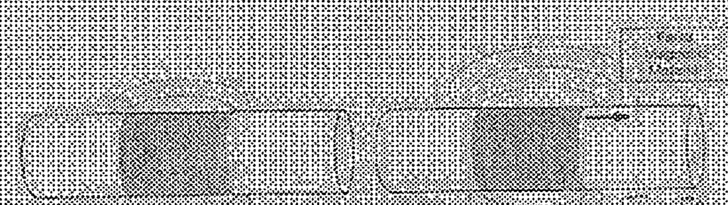


Fig. 50

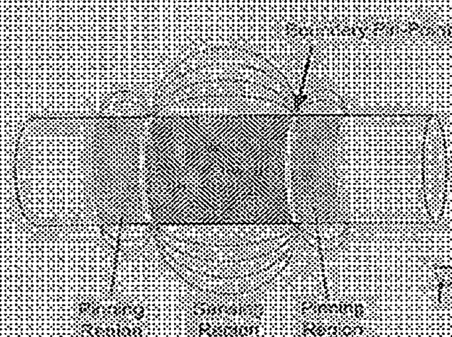


Fig. 51

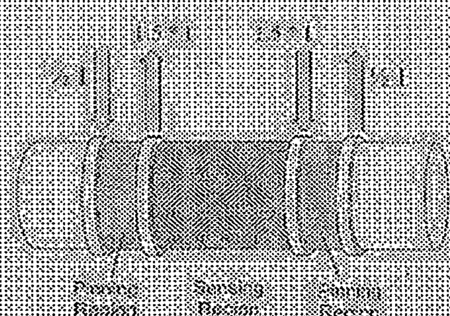


Fig. 52

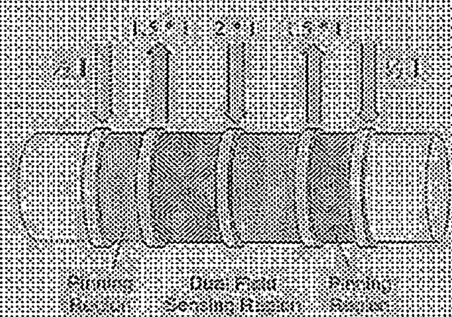


Fig. 53

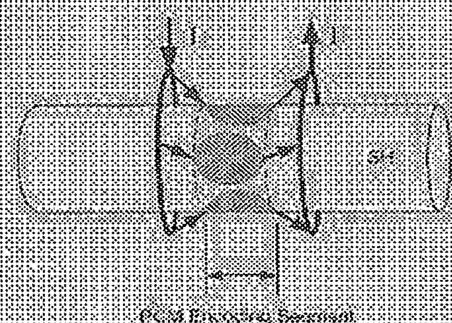


Fig. 54

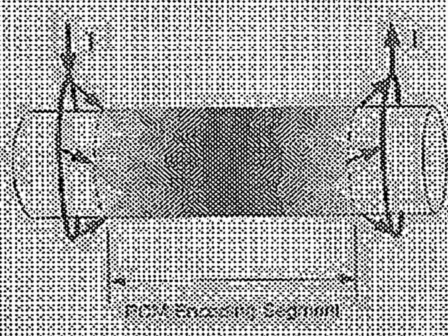


Fig. 55

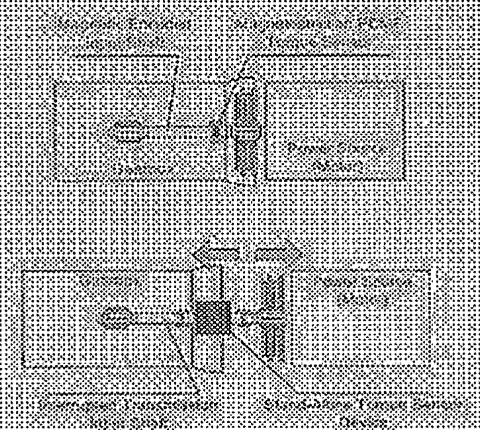


Fig 56

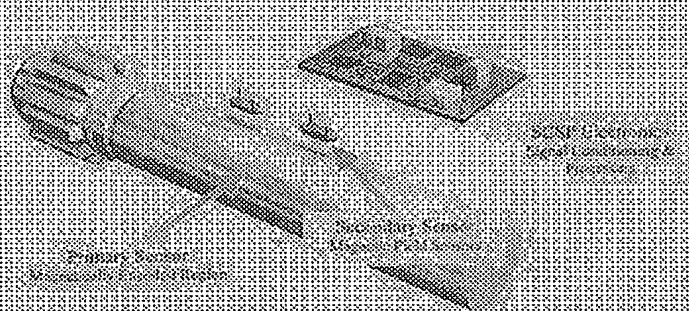


Fig 57

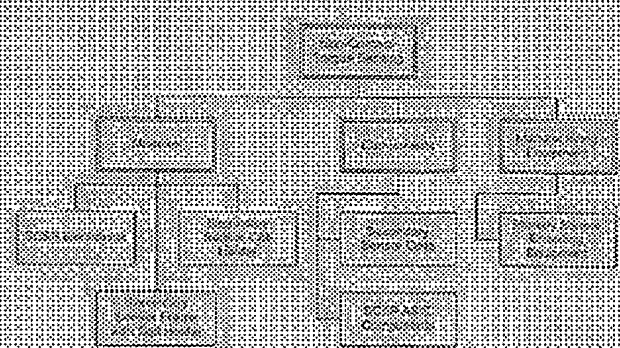


Fig 58

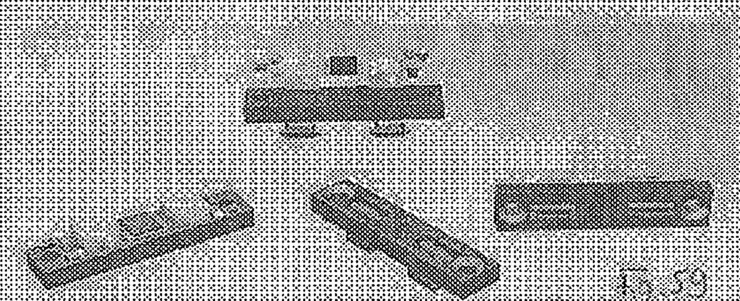


Fig 59

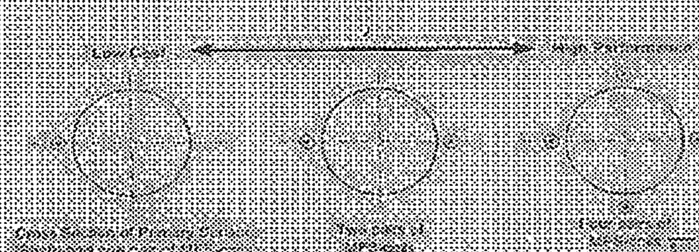


Fig 60

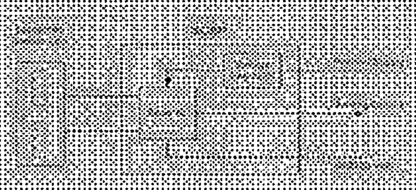


Fig 61

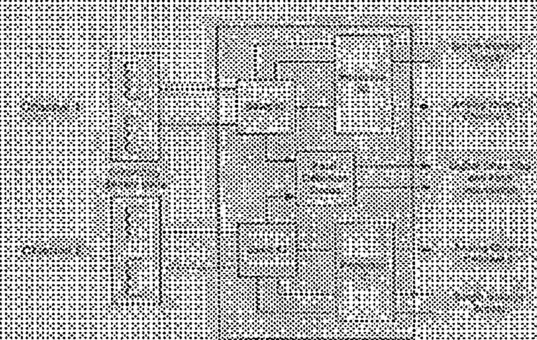


Fig 62

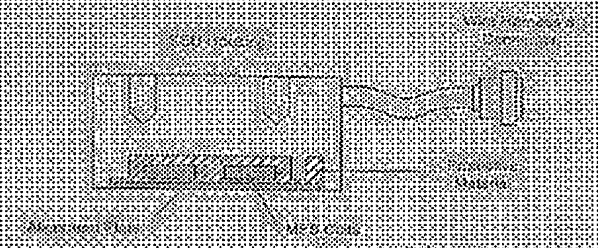


Fig 63

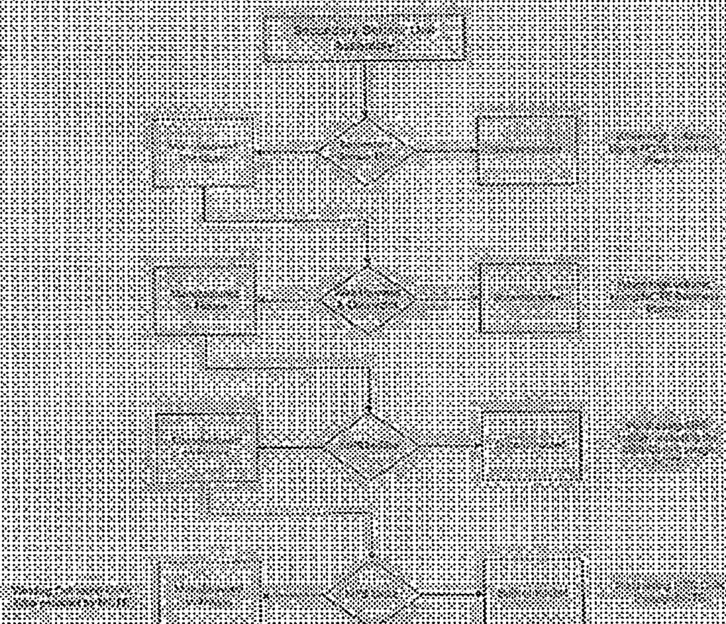


Fig 64

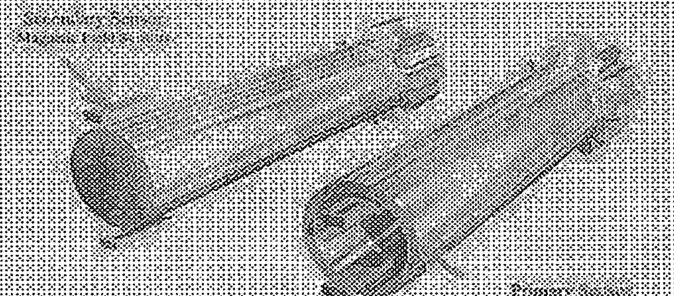


Fig 65

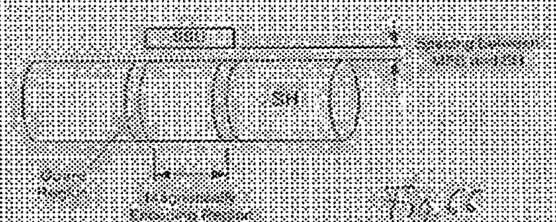
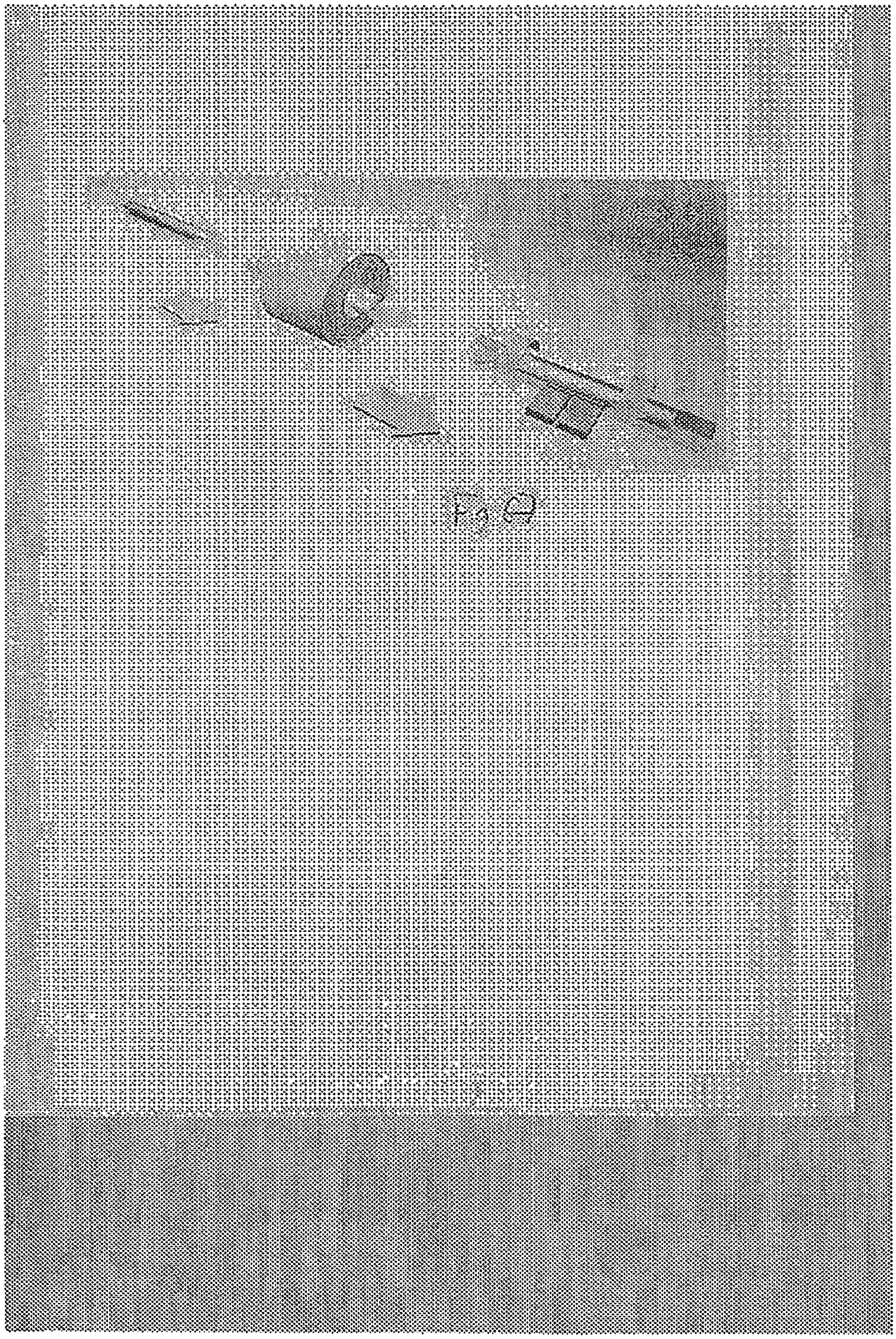


Fig 66



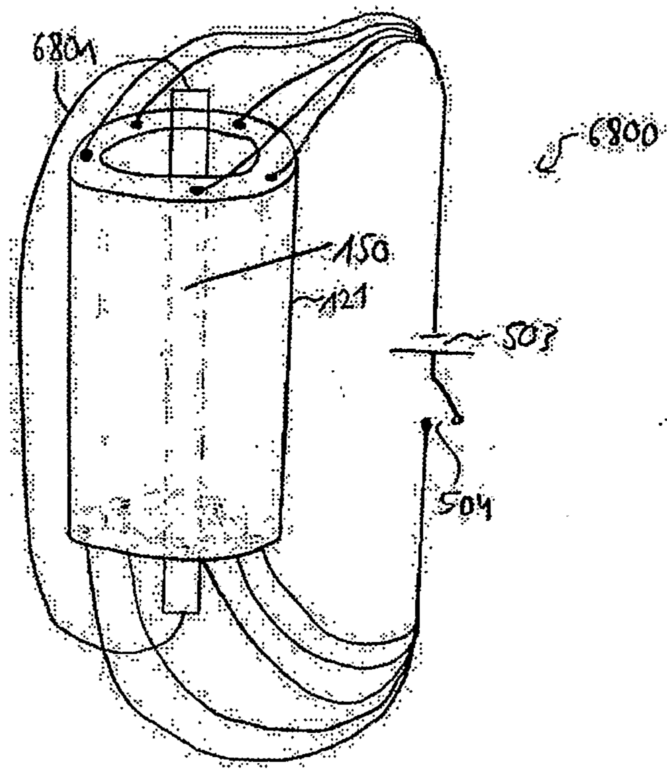


Fig. 68

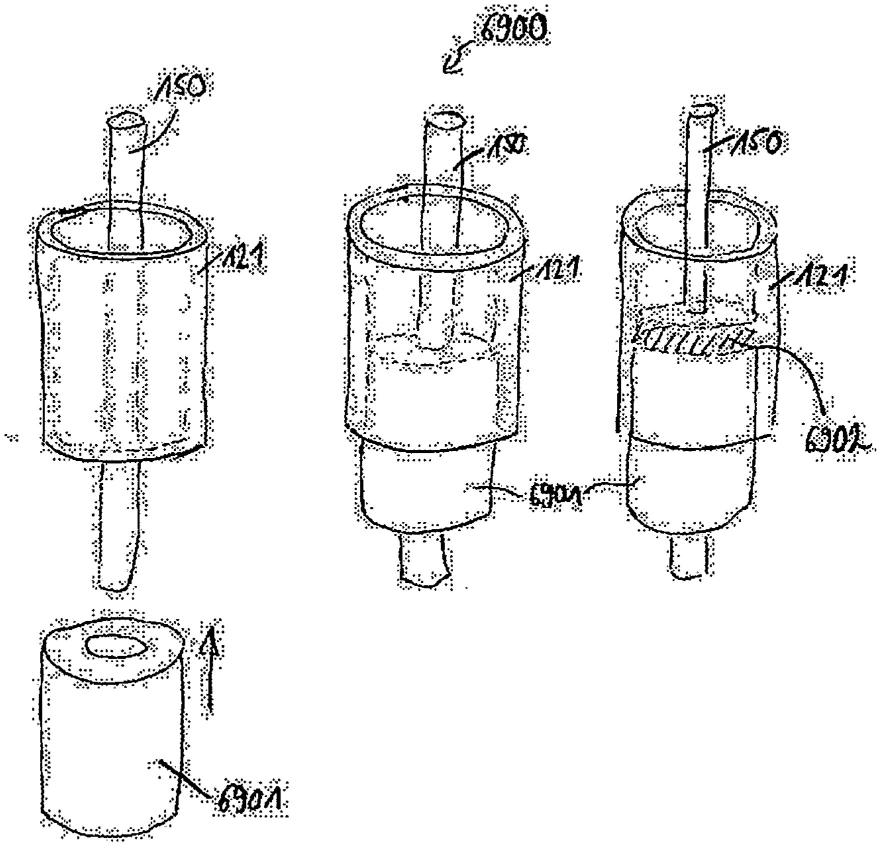


Fig 69

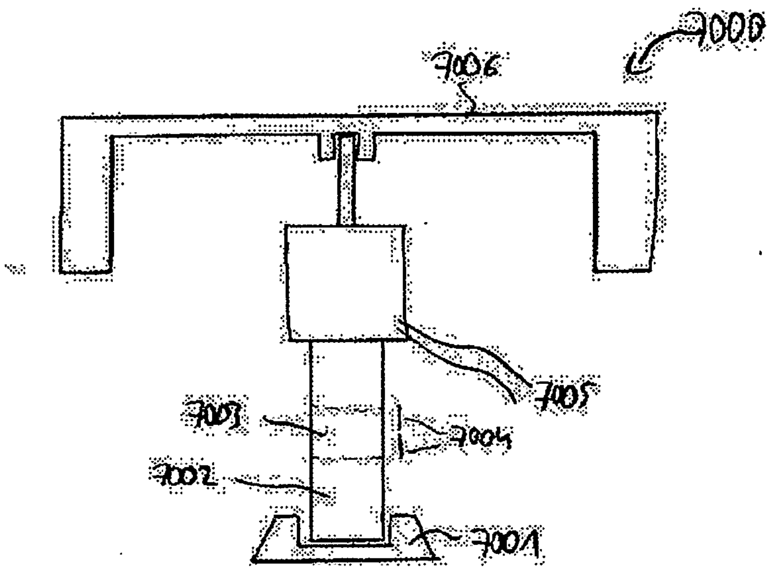


Fig 70